NAVAL FACILITIES ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

Special Publication
SP-2081-SHR

AIRFIELD PAVEMENT VOID DETECTION TECHNOLOGY

by

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April 2000

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EXECUTIVE SUMMARY

Several recent accidents involving aircraft punching through pavements have prompted the Naval Facilities Engineering Command (NAVFAC) to task the Naval Facilities Engineering Service Center (NFESC) to address this problem. Initially, NFESC and NAVFAC's Southern Division completed a successful void detection survey at NAS Pensacola [1], and prepared a draft Interim Policy and Technical Guidance (IP&TG) that was issued by NAVFAC on 23 March 2000. The current report is a continuation of this effort, and concentrates on assessing the overall problem and completing a state-of-the-art survey of available applicable technologies.

A review of airfield pavement failures was conducted for the Navy, Army and Air Force, and several accidents were found where aircraft had punched through pavements. Other Navy pavement failures were reported, which fortunately did not involve any aircraft, although some of them happened in active airfield pavements. Finally some commercial failures were also reviewed.

Since many failures are known to have resulted from subsurface voids caused by soil erosion near drain pipes, a survey was conducted of all Navy and Marine Corps airfields in an attempt to quantify the magnitude of the potential problem. On average, the airfields surveyed have about 15 drainage structures crossing under airfield pavements, compared to 33 drainage structures for NAS Pensacola.

A review of the state-of-the-art non-destructive technologies applicable to void detection under airfield pavements was completed. Several electromagnetic, transient-load, and miscellaneous techniques were addressed. The experience of several Government agencies, State Departments of Transportation, academia, and private firms on all available applicable techniques was gathered and summarized. The following are conclusions derived from their shared knowledge:

1. No single technique is currently capable of providing a complete solution to the void detection problem.
2. A combination of technologies can, however, provide a cost-effective, reliable methodology to minimize the potential for accidental airfield pavement failure due to subsurface voids.
3. The optimum technology combination at the current time is a combination of visual, Heavy Weight Deflectometer (HWD) and Dynamic Cone Penetration (DCP) techniques, which can be completed by a single operator. The DCP can be replaced by an Electronic Cone Penetration (ECP) or a Standard Penetration Test (SPT), but these techniques require additional manpower.
4. Complementary technologies include video taping and Ground Penetrating Radar (GPR). Video taping was shown to allow for the detection of pipe failures indicative of potential void problems, and even the detection of actual voids. GPR is very useful for determining pavement layer thickness (for use in HWD structural evaluation), and location of drain pipes (assuming favorable low conductivity subgrade characteristics).

5. Promising technologies include Rolling Weight Deflectometer (RWD), High Speed Deflectograph (HSD), Rolling Dynamic Deflectometer (RDD), GPR, and Infrared Thermography. It is currently not recommended to use these technologies as primary detection tools, but further development may increase their reliability for such application.
6. In some cases, e.g. when the area to investigate is very significant, using the HWD to perform a thorough coverage may not be possible. In that case, it is recommended that: (1) the HWD be used at any critical location within the area of concern, (2) the GPR be used to complete coverage of the area in an attempt to identify subsurface anomalies (assuming soil characteristics allow its use), (3) the HWD be used again at the discrete locations where the GPR identifies anomalies, and (4) DCP testing be completed where weaknesses were confirmed by the HWD.

This document further supports considering the HWD as a primary tool in detecting voids and determining the effect of the voids on the pavement load carrying capacity. It is recommended that a void detection survey be performed on the same cycle as the structural evaluation (every 8 years), and by a member of the Tri-Service Airfield Pavement Team until the technology is further disseminated.

It is also recommended that a DCP and a small portable GPR be purchased for further evaluation by NFESC. If successful, these two devices should be made available to all three EFDs performing structural evaluations.

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1. INTRODUCTION

1.1. BACKGROUND

On 20 May 1999, a T-34C aircraft fell into a 12-inch deep hole that formed in taxiway LT2/3 (or TWA3), between runway features RW25R and RW25L, at NAS Pensacola. This pavement failure was due to local base and subgrade erosion from a leaking drain pipe under the taxiway. In July 1999, the Naval Facilities Engineering Service Center (NFESC) was tasked by the Naval Facilities Engineering Command (NAVFACENGCOM or NAVFAC) to determine the extent of potential voids near all drain pipes under the runways, taxiways and aprons. NFESC, in cooperation with NAVFACENGCOM Southern Division, and with support from NAS Pensacola, completed an assessment of the airfield pavements above drain pipes and found several other areas with loose subgrades, and some with actual voids. Several destructive and nondestructive techniques were used in detecting the voids, and the reliability of each technique was assessed. A final report was completed by December 1999 [1], and most deficient areas have already been repaired.

Based on this and other related incident at various Navy bases, on 23 March 2000 NAVFACENGCOM issued an Interim Policy and Technical Guidance (IP&TG) to insure that the problem is addressed at all Navy and Marine Corps airfields (see Appendix A). This IP&TG was based on work by NFESC and the Tri-Service Pavement Group based on the NAS Pensacola report. The Tri-Service Pavement Group is the Navy leading technical group for airfield pavements. It includes representatives from all NAVFAC Engineering Field Divisions, NAVFAC HQ, NAVFAC Public Works and Criteria Office, U.S. Army (Engineer Research and Development Center - ERDC, Waterways Experiment Station – WES, Geotechnical Branch), and Air Force (Air Force Civil Engineer Support Agency – AFCESA, and Air Force Research Laboratory – AFRL).

1.2. SCOPE

NFESC was tasked by NAVFAC to determine the extent of the problem Navy wide. The current report includes a survey of DOD airfield pavement problems due to voids. Since most problems are related to leaky drain pipes, the extent of drain pipe crossings under Navy airfield pavements was also completed.

NFESC was also tasked to assess all existing current technology applicable to void detection under pavements. A comparative assessment of some of the technologies was already completed in the NAS Pensacola report. Previous state-of-the-art reviews on potentially applicable technologies, such as pavement testing techniques, were gathered [2-7]. The present report summarizes the current state-of-the-art in void detection technology.

2. EXTENT OF THE PROBLEM

2.1. RECENT NAVY PAVEMENT FAILURES

Voids under Navy airfield pavements due to sinkholes or erosion have recently resulted in accidents or concerns at the following locations:

- MCAS Pendleton (March 2000), where a 6-foot diameter, 4-foot deep sinkhole surfaced on the runway (Figure 1). The pavement included 7 inches of AC on 12 inches of Class II road base, over a hard sandstone strata. It appears that the sandstone was washed away by a fluctuating water table. Repair was completed with a 12-ft by 30-ft full-replacement patch.

- NAS Pensacola (May 1999), where the front gear of a T-34C punched through the pavement on taxiway LT2/3 (Figure 2). The nose gear came to rest about twelve inches below the pavement surface, resulting in propeller impact on the pavement. This failure was due to a leaky storm drain pipe that eroded part of the subgrade [1]. In this incident, voids were detected using the Heavy Weight Deflectometer (HWD) [1]. The Air Force Research Laboratory (AFRL) supported the Navy in determining the extent of some of the void using a Ground Penetrating Radar (GPR) system [1, 8]. The Air Force Civil Engineer Support Agency (AFCESA) verified the voids and weak areas using an Electronic Cone Penetrometer (ECP).

- OLF San Nicolas Island (March 1998), where both main gears of an F-4 punched through an AC pavement (Figure 3), and where additional sinkholes in the runway and nearby were found (Figure 4). The aircraft was being towed from ramp to hangar for maintenance and to avoid obstacles on left side of taxiway centerline the aircraft was towed through an unmarked asphalt area. The aircraft tow was stopped just prior to a concrete pad, which was the location of the failure. In this case the pavement was very weak, the base was saturated and had been eroded [9].

- NAS Jacksonville (1998), where several aircraft punched through an asphalt pavement (Figures 5 and 6). The taxiway where the incidents occurred had only 3 inches of deteriorated asphalt, on top of a leaky old clay pipe. The taxiway has since been reconstructed.

- Ban Utapao airfield, Thailand (June 1997), where a fuel pipe leak was suspected to have affected the subgrade, although no pavement degradation was found [10]. Although it was confirmed by videotaping that the pipe was broken, it was not in use, and the load carrying capacity was not affected.

- NAS Whidbey Island (since 1997), where voids are known to exist under Taxiway B and D, at the joints between PCC and AC pavement surfaces. The joint seals failed and water intrusion had caused washing out of supporting soils. Voids are also suspected under Taxiway A, where a leaking 18” drain pipe has resulted in several 12½ by 15 ft. concrete slabs cracking into two pieces. About 18000 feet of pipes are located under taxiways and parking aprons.

- NAS Moffett Field (August 1986), where a P3C was being towed from a designated taxiway to a paved area (NASA parking apron) when its landing gear broke through the pavement. The paved area was structurally inadequate (due to inadequate subgrade support) for this type of aircraft. Attempts to move the aircraft before taking any steps necessary to ease the removal, such as defueling and laying steel mats, resulted in further sinking. The event summary from the Naval Safety Center [11] indicates that the initial attempts to free the aircraft could have resulted in damage to the nose strut due to excessive force being applied. Furthermore, injury to personnel could have occurred had a tow strap or chain parted from the port main landing gear.

- NAS Corpus Christi (1985), where a C-141 punched through a concrete pavement (Figure 7) [12]. Ninety five percent of the slabs in that area were shattered, and the aircraft was not supposed to use it. The subgrade was a highly erodible silty sand.

2.2. RECENT AIR FORCE PAVEMENT FAILURES

The Air Force also has had airfield pavement failures due to sinkholes or erosion, in particular at the following locations:

- Pope AFB (October 1999), where a sinkhole formed near Taxiway Alpha, and where some soft soil was found under the pavements using the ECP from AFCESA [8].

- Thule AFB, Greenland (July 1999), where settlement and loss of subgrade support due to permafrost thawing resulted in depressions along the runway shoulders and concerns about the structural integrity of the runway [13]. GPR data showed no discernible voids under the runway itself. Developing a comprehensive airfield drainage plan was among the recommendations.

- Andrews AFB (April 1999), where concrete slabs settled about 2 inches over a leaky drain pipe [8]. The drain pipe was about 20 feet deep. Soft areas were detected using GPR and verified by ECP. The settlement was repaired by injecting a polyurethane foam. Some excess pumping resulted in excessive compensation, which required later grinding.

- Peterson AFB (February 1997), where weak areas were found under an apron due to a ruptured storm drain [8]. Both the GPR and HWD were used to detect the weak areas or voids. However, in the HWD detection only output from sensor D1 was used. Output from all seven sensors is necessary to perform an accurate detection [1].

- Hurlburt Field (May 1996), where HWD and GPR were used to detect weak areas under a hangar and building 90810 due to a water pipe rupture [8]. Dynamic Cone Penetrometer (DCP) testing indicated weaker but still satisfactory subgrade at a couple of locations.

- Travis AFB (April 1995), where a severe water line failure prompted concerns about the potential of voids under Taxiway N [8]. GPR located voids under the asphalt shoulder near the taxiway. These were verified by coring.

- Eglin AFB (March 1995), where voids were suspected under two ramps and one taxiway [8]. GPR and HWD located large voids near the storm drain inlet. Coring was used to verify the voids.

2.3. OTHER NAVY RELATED CONDITIONS

Other Navy airfields have experienced void related problems that have not affected their operations. The information reported below was gathered from the local Public Work Centers and Engineering Field Activities.

- MCAS Iwakuni. Known voids are present under an asphalt pavement near a wharf (away from the airfield). One of the voids was verified by coring. The NFESC technician testing the airfield was able to pinpoint the voids using the HWD data he was gathering. In the generated data file, the far right column was the output of sensor D7, which should remain fairly constant since D7 represents the subgrade. If D7 is variable, it means lack of constant support under the slab. Most of the data for the wharf showed D7 around 10 to 15 mils. When the D7 reading jumped to around 40 mils, this indicated a general lack of support under the slab (i.e. a void). This pavement is currently being investigated to determine its capacity to carry mobile cranes.

- NAS Key West. During the past twelve years there has been no evidence of void problems associated with drainage structures. However, an old sea plane ramp used for helicopters had some M&R recently completed and there were small pockets of voids under the 11” to 15” PCC slabs. They are believed to have been the result of tide action. In addition, there are numerous depressions in the asphalt concrete pavement of an abandoned taxiway that may be brought back into service. These depressions do not appear to be associated with drainage structures. Airfield pavements are constructed with limestone rock base and the subgrade is not similar to other areas of Florida that have karst conditions.

- NAF Mayport. During the past 23 years there has been no evidence of void problems associated with drainage structures. One location at the airfield (aircraft parking apron) was built on an area that was built up using dredge material. Above the location of an old drainage ditch, a one-inch deep by about 200' depression appeared on the apron approximately 14 years after construction. This depression is believed to be the result of consolidation of loose soils (dredge material) and decay of old vegetation in and along the old drainage ditch. Airfield pavements are constructed with limestone rock base and the subgrade is sand. The water table is very high under the entire airfield.

- NAS Jacksonville has had problems associated with drainage structures every year for at least the past ten years. Typically some type of pipe repair is completed every year, which includes pipe lining. However, even though the pipe stops leaking after repair, whatever void had formed around the drainage structure is still there and tends to work its way up to the pavement where collapse or settlement occurs. The sea plane area and parking has numerous depressions and voids and is suspected of being built on a hazardous waste site. At the present time NAS Jacksonville is contracting to have all its drainage structures video taped. All pipes are being cleaned out, and the material removed is being tested for contamination. When the task is completed, results will go to SouthDiv for a design/build repair contract. This repair contract was initially approved by CINCLANTFLT for three million dollars. However, since the requirement to test the material coming out of the drainage structures has slowed the progress of the video taping, money has not been re-approved to date.

- NAS Whiting Field. Several drainage structures go under airfield pavement on North Field. There is no evidence of surface depressions at this time. However, there is a natural sinkhole at the west end of the abandoned runway. At the South Field there is no surface evidence of depressions or any other distress that would cause any concern relative to voids at this time.

- NAS Alameda and NAS Adak. Both bases are now closed, however many years prior to closure both locations experienced large voids under their pavements. No aircraft mishap occurred as a result of these voids, although in both cases major damage could have occurred. At Alameda a drainage structure was adapted with flood gates (inlet covers) so that when the tide came in, the covers would automatically close to prevent water from flowing back up to the airfield (which would cause tide water to “pond” at the outlet). For some reason the covers were cut off allowing the water to flow in and out twice a day causing failure at the joints of the structure. When detected, the void was approximately four feet in depth and covered about 300 square feet. At Adak a void was located at the edge of a parking apron (approximately two feet in depth) and was repaired by “mud jacking”. The cause of this void was unknown.

- In early 1999, several sinkholes developed along the North Wharf area at NAVSTA Everett, near an abandoned storm line (Figure 8). This area had developed a sinkhole in 1997, which was excavated, compacted, and paved. Additional sinkholes developed in the same area in 1999, and an investigation determined that the most likely cause was an abandoned 36" storm water outfall. This abandoned outfall was filled with concrete, and the active storm outfall was slip lined. This has hopefully resolved the cause of the problems.

2.4. OTHER INCIDENTS

The U.S. Army Safety Center and ERDC-WES were also contacted for possible incidents at Army airfields. None was reported.

While the database is limited, other pavement failures have also been experienced in commercial airfields:

- On 2 May 1990, at the Manchester, New Hampshire Airport, the landing gear of a DC-9 carrying a full load of passengers punched through the pavement while approaching the gate [14] (Figure 8). The damage to the landing gear, fuselage, and fuel system approached $500K. Failure was due to a 6 by 6 by 8 feet void under the pavement, created by a leaky 40-year-old storm water drainage system. The photo was provided by the Lund Institute of Technology, Sweden, and also by EnTech Engineering, Inc.
- Natural sinkholes appeared on runway 8-26 > at Capital City Airport in Harrisburg, Pennsylvania, in 1984 (Figure 8) [15]. The airport > sits > atop > a large limestone formation near a river. Over time, as the river > rises > and > falls, it dissolves some of the limestone creating "solution > cavities". > These > tend to grow in periods of heavy rainfall and flooding. Several sink> holes (at least one in the runway that was approximately 5' diameter by 3' deep) have > opened over the years, fortunately no airplane has ever gone in one (Figure 8) [15]. Mr. John Rice of the FAA indicated the airport hired a > firm to > perform > ground penetrating radar to locate potential sinkholes, and to monitor the situation with acoustic emissions > technology [15], neither of which appeared to be too successful. Mr. > Robert Shields, Engineering Director at Harrisburg International Airport, which includes Capital City Airport, has indicated they continue to have a sinkhole problem and filling of sink holes is performed on a regular basis.
- Mr. Fran Strouse, Delta Airport Consultants, indicated that numerous sinkholes also occur at Lehigh Valley International Airport and University Park Airport, both of which are in Pennsylvania. The problem at these locations is the washing out of material (i.e. clay) from the limestone beds and washing out of the limestone "solution" resulting from limestone bed fractures (similar to that at Capital City Airport). Typical procedures/methods used for detecting sinkholes have included GPR and Electrical Resistivity tools (both with limitations and not too successful in locating sinkholes), destructive testing, and investigation and use of Aerial Photo Interpretation. Aerial Photo Interpretation (stereoscopic imagery) has been fairly successful with this type of sinkholes. This procedure indicates a high probability of sinkholes where lighter color of mottling is detected and where fracture traces are located.
- In the mid 1980's, at Dekalb-Peachtree > Airport in Georgia, > > a small twin-engine airplane was > taxiing when > the main gear punched through the pavement. Mr. John Rice of the FAA indicated that an underground storm drain > pipe > was > leaking and it undermined the pavement. No fatalities or injuries occurred but damage to the plane was substantial.

2.5. MAGNITUDE OF EXISTING CONDITION IN NAVY AIRFIELDS

A request for drawings and supporting data for drainage structures located beneath airfield pavements was sent to 37 Naval Air Stations, Marine Corps Air Stations and Naval Stations with airfields. Twenty-five of the 37 stations responded which represent 36 of the 66 airfields. Drawings and data submitted by the stations greatly varied in type of information, detail, clarity, and so on. Due to the wide range of data, only an approximate number of crossings under runways and taxiways was determined. To establish an estimate of the linear feet of drainage structures that cross beneath runways and taxiways, the crossings under runways were assumed to be about 200 feet, and the crossings under taxiways were assumed to be about 150 feet. The exact length of each crossing will vary due to the angle at which it crosses the pavement, actual width of the pavement, and so on. Number of crossings and estimated linear feet for each airfield are shown in Tables 2-1, 2-2 and Figure 9**.**

In addition to runways and taxiways, numerous drainage structures cross under parking aprons. The number and estimated linear feet of drainage structures crossing under parking aprons was not determined at this time. However, personnel at each airfield (Public Works, Engineering and/or Air Operations) generally know the number and where drainage structures cross at their specific station.

Based on this distribution it is estimated there are approximately 1170 drainage structures which cross under runway and taxiway pavements throughout all 66 Navy and Marine Corps Air Stations. It was also estimated that 36% (about 420) of these are under runways and 64% (about 750) are under taxiways. These estimates indicate there is approximately 200,000 linear feet of drainage structures located beneath runway and taxiway pavements. Estimated linear feet per station are also shown in Tables 2-1 and 2-2. When drainage structures located beneath parking aprons are added to the runway and taxiway estimate, it is expected that the total linear feet of drainage structures beneath airfield pavements may exceed 500,000 feet.

TABLE 2-1. DRAINAGE STRUCTURES PER AIRFIELD

Airfields	Number of drainage structures								
	1-5	6-10	11-15	16-20	21-25	31-35	36-40	51-55	61-65
Number of airfields	11	14	11	9	7	5	5	2	2
Percent of airfields	17	21	17	14	10	7	7	3.5	3.5
Approx. linear feet per airfield	500	1250	2150	3000	3600	5100	5800	10200	12100

TABLE 2-2. CROSSINGS UNDER RUNWAYS AND TAXIWAYS AT ALL BASES.

No	Installation	Type	Runways		Taxiways		Comments
			Amount	Feet	Amount	Feet	
1	Atlanta	NAS	0	0	2	300	AF R/W Pavement
2	Atsugi	NAF	0	0	7	1050	Japanese Pavement
3	Barin	NOLF	1	200	2	300	
4	Barking Sands	PMRF					
5	Beaufort	MCAS					
6	Bravo	NOLF					
7	Brewton	NOLF					
8	Brunswick	NAS					
9	Cabaniss	NALF	x		x		insufficient info
10	Camp Pendleton	MCAS	0	0			
11	Cherry Point	MCAS	16	3200	18	2700	unclear
12	China Lake	NAWS					
13	Choctaw	NOLF	x		x		unclear
14	Corpus Christi	NAS	9	1800	13	1950	
15	Coupeville	NOLF					
16	Diego Garcia	NSF					
17	El Centro	NAF	10	2000	4	600	
18	Evergreen	NOLF					
19	Fallon	NAS					
20	Fentress	NALF	2	400	4	600	
21	Fort Worth	NAS	2	400	8	1200	
22	Futenma	MCAS					
23	Guantanamo Bay	NAS	6	1200	4	600	
24	Hawaii	MCBH					
25	Holley	NOLF	1	200	0	0	
26	Iwakuni	MCAS	2	400	15	2250	
27	Jacksonville	NAS	9	1800	15	2250	
28	Keflavik	NAS	x		x		unclear
29	Key West	NAS					
30	Kingsville	NAS	24	4800	30	4500	
31	Lakehurst	NAEC					
32	Lemoore	NAS	24	4800	40	6000	
33	Mayport	NAF	1	200	13	1950	unclear

TABLE 2-2. CROSSINGS UNDER RUNWAYS AND TAXIWAYS AT ALL BASES (CONTINUED).

No	Installation	Type	Runways		Taxiways		Comments
			Amount	Feet	Amount	Feet	
34	Meridian	NAS					
35	Miramar	MCAS	5	1000	10	1500	
36	Misawa	NAF	0	0	12	1800	AF R/W Pavement
37	New Orleans	NAS	16	3200	x		No taxiway data
38	New River	MCAS					
39	Norfolk	NAS	2	400	34	5100	
40	North Island	NAS					
41	Oceana	NAS	x		x		unclear
42	Orange Grove	NALF					
43	Patuxent River	NAS	17	3400	20	3000	
44	Pensacola	NAS	11	2200	22	3300	
45	Point Mugu	NAS					
46	Quantico	MCAF					
47	Roosevelt Roads	NAS					
48	Rota	NS					
49	San Clemente Isl.	NALF					
50	San Nicolas Island	NOLF					
51	Santa Rosa	NOLF	10	2000	9	1350	
52	Saufley	NOLF	6	1200	13	1950	
53	Sigonella	NAS	x		x		unclear
54	Silverhill	NOLF	1	200	0	0	
55	Souda Bay	NAS					
56	Spencer	NOLF					
57	Summerdale	NOLF	x		x		unclear
58	Waldron	NALF	x		x		insufficient info
59	Washington	NAF	0	0	6	900	AF Pavement
60	Whidbey Island	NAS	0	0	8	18000	unclear
61	Whitehouse	NOLF					
62, 63	Whiting Field N & S	NAS	6	1200	16	2400	
64	Willow Grove	NAS	3	600	8	1200	
65	Wolf	NOLF	1	200	2	300	
66	Yuma	MCAS					

Notes: Length associated with runways is assumed to be 200' each however actual would average slightly higher due to some drainage structures crossing at various angles. Length associated with taxiways is assumed to be 150'. This takes into account the 150' and 75'taxiways and drainage structures which cross at various angles.

3. ELECTROMAGNETIC TECHNIQUES FOR VOID DETECTION

Several of the non-destructive techniques detailed below are based on generating an electromagnetic wave, and measuring its reflection from a subgrade discontinuity in electric conductivity. Tables 3-1 and 3-2 indicates the typical frequencies and wavelengths used per wave type, and per application.

TABLE 3-1. ELECTROMAGNETIC SPECTRUM BY WAVE TYPE

RADIATION TYPE	FREQUENCY RANGE (Hz)	WAVELENGTH RANGE (M)
Gamma rays	$10^{20} – 10^{24}$	$< 10^{-12}$
X rays	$10^{17} – 10^{20}$	$3.\ 10^{-12} – 3.\ 10^{-9}$
Ultra Violet	$10^{15} – 10^{17}$	$3.\ 10^{-9} – 300.\ 10^{-9}$
Visible spectrum	$4.\ 10^{14} – 7.5\ 10^{14}$	$400.\ 10^{-9} – 750.\ 10^{-9}$
Near infrared	$10^{14} – 4.\ 10^{14}$	$0.75\ 10^{-6} – 3.\ 10^{-6}$
Infrared	$10^{13} – 10^{14}$	$3.\ 10^{-6} – 30.\ 10^{-6}$
Microwaves	$10^{11} – 10^{13}$	$30.\ 10^{-6} – 3.\ 10^{-3}$
Radio waves	$< 10^{11}$	$> 3.\ 10^{-3}$

Adapted from: http://www.scimedia.com/chem-ed/light/em-spec.htm and http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html

Notes: the speed of light is $3.\ 10^{8}$ m/s (wavelength = speed of light / frequency)
Millimeter waves have wavelengths around 1 mm (between 0.3 and 10 mm), frequencies around 300 GHz (30 to 1000 GHz) and overlap between micro and radio waves.

TABLE 3-2. ELECTROMAGNETIC SPECTRUM BY APPLICATION

APPLICATION	FREQUENCY RANGE (Hz)	WAVELENGTH RANGE (M)
Millimeter wave	$3.\ 10^{10}$ - 10^{12}	$0.3\ 10^{-3} – 10.\ 10^{-3}$
GPR	$10^{7} – 10^{10}$	0.03 - 30

3.1. GROUND PENETRATING RADAR (GPR)

RADAR is an acronym coined in the early 1930's for RAdio Detection And Ranging. Ground Penetrating Radar has been around since 1929, but commercial systems have only been available since 1972 [16]. NFESC (formerly the Naval Civil Engineering Laboratory - NCEL) has studied GPR since the early 1980's [17].

GPR works by transmitting a short radar pulse, typically from the transient voltage pulse from an overloaded avalanche transistor. The pulse reflection is measured, and is dependent on the soil electrical conductivity. Objects or areas in the ground with different electrical properties will reflect the pulse differently, and appear as anomalies.

Soil penetration depends on soil type and antenna type. Soil moisture, as well as high clay soils, will quickly attenuate the radar signal and decrease its performance (i.e. dry sandy soils are best). The GPR detects variations in conductivity, or dielectric constant (Table 3-3). The dielectric permitivity describes the extent to which the electric charge distribution in a material can be distorted by an electric field. The conductivity described the ability of the material to conduct electrical current, and is described in reciprocal ohms, or mhos, now called siemens (S). If the soil is saturated, or if a pocket of loose soil is sought (within more compacted soil of the same type), variations in conductivity may not be discernible.

TABLE 3-3. DIELECTRIC CONSTANT AND CONDUCTIVITY FOR TYPICAL SOIL MATERIALS

MATERIAL	DIELECTRIC CONSTANT	CONDUCTIVITY (mS/meter)
Air	1	0
Ice	3 – 4	0.01
Dry sand	3 – 5	0.01
Asphalt concrete	3 – 5	-
Granite	4 – 6	0.01 – 1
Concrete	6 - 11	0.01 – 5
Fresh water	80	0.5
Saturated sand	20 – 30	0.1 – 1
Limestone	4 – 8	0.5 – 2
Shales	5 – 15	1 – 100
Silts	5 – 30	1 – 100
Clays	5 – 40	2 – 1000
Salt water	80	3000

The GPR can discern objects underground whose diameter is, in general, no less than 1/12 of the depth at which it is located. High frequency antennas, in the order of 1 to 2 GHz, produce the best resolution (e.g. can find small objects), but can only penetrate a few inches. For example, just below a 12-inch concrete pavement, the smallest diameter of pipe that can be identified would be 1 inch (e.g. with a 900 MHz antenna and center frequency). Low frequency antennas, in the order or 10 to 200 MHz, can penetrate tens of feet, depending on soil conditions, but may not be able to locate small objects, such as small diameter pipes. For airfield pavements, where the depths or interest vary from 1 to 20 feet, two antennas may be required, one around 900 MHz, and one around 200 MHz. At a depth of about 12 feet, which is probably about the deepest of interest for most pavements, the smallest diameter of pipe that could be found would be 1 foot (e.g. with a 200 MHz antenna). At greater depths, only large discontinuities would be found (e.g. 13 feet object with a 12 MHz antenna). Under optimum conditions, a 12 MHz antenna could detect large objects at depth of 200 ft or more.

Although the GPR is supposed to be able operate at a single frequency, it typically generates a broad band signal (e.g. from 75 to 300 MHz for a center frequency of 150 MHz). As a result it may not be able to differentiate between closely spaced objects (e.g. two or more pipes).

Postprocessing can include automatic waveform interpretation [18], and three-dimensional (3D) imaging [19, 20].

GPR systems can be mounted on vans or carts, and generate a continuous record of soil cross sections, with a given depth and width (Figures 10 to 13). Portable, user-friendly systems exist, that can be readily transported and deployed [21]. These can provide real time soil cross sections for immediate analysis, or for storing on videotape for later evaluation. The raw signal can also be postprocessed to better identify anomalies.

In any case, proper interpretation of GPR output requires considerable operator experience, and it is an art as well as a science. Excessively optimistic claims by GPR providers have led to confusion and disappointment on the GPR success rate. As will be shown below, GPR has been successful between 25% and 75% of the time, depending on the operator, the system, and the site.

3.1.1. GPR ADVANTAGES

GPR results cannot be directly related to load carrying capacity, in contrast to the HWD. The GPR may identify areas that are different, i.e. anomalies in the pavement, but cannot quantify their impact on the load capacity. However, the advantage of the GPR resides in its ability to process a large amount of data quickly, hence covering a large area while producing a real time output. In addition, the GPR can be useful in determining pavement thickness, and drain pipe location, thus complementing the HWD data. Other researchers have proposed using the GPR as a complementary tool to the HWD [22].

3.1.2. GPR SURVEY

A comprehensive survey was completed to identify providers and users of state-of-the-art non-destructive technology (NDT) applicable to void detection. Particular emphasis was put on the GPR, and its reliability in detecting voids under a pavement. A search located over 50 GPR providers (Appendix B). Most providers have a web site, which can be reached by doubleclicking on the web address included after each. The following is a summary of the users contacted and their satisfaction with various NDT technologies, and the GPR in particular.

3.1.2.1. USGS

The U.S. Geological Survey maintains a variety of high quality, state-of-the-art scientific capabilities that include GPR. The USGS operates its own instruments and software, which were purchased from major vendors (see Appendix B) and slightly modified. Besides voids, their GPR has been used to detect oil contamination, although this was hampered by signal attenuation due to saturation [23].

Additionally, the USGS conducts geophysical analyses that encompass a broad range of techniques seeking to image the region beneath the Earth's surface via interpretation of physical parameters, waves, or fields measured at the surface. Physical quantities measured include gravitational acceleration, geomagnetic field, rock magnetism, electrical conductivity, electromagnetic fields from both natural or manmade sources, seismic waves from explosions or earthquakes, heat flow, and others. These are addressed later.

3.1.2.2. USDA

The Technology Transfer Information Center (TTIC) helps to promote the rapid conversion of federally-developed inventions into commercial products by "getting the results of research into the hands of those individuals and organizations who can put it into practical use." The TTIC is part of the National Agricultural Library of the U.S. Department of Agriculture.

Recently, the Federal Laboratory Consortium's State and Local Governments Committee, the Trenchless Technology Center, and the Technology Transfer Information Center sponsored a joint project on Utility Locating Technologies. The project issued a statement of need (SON), which can be found in the web at http://www.nal.usda.gov/ttic/utilfnl.htm. The SON addresses "an issue of significant national importance - the current and increasing potential for damage to underground utility systems caused by other excavation and utility installation/repair activities." This SON "seeks novel solutions to the problem of effective location of all types of underground utilities under the variety of site conditions found in urban areas." Utility location technology overlaps void detection technology, and any knowledge acquired through the SON should be of interest to the current report.

Some of the technologies addressed in the SON include:

- radar (e.g. ground penetrating radar),
- seismic waves,
- acoustic waves (laser-induced acoustic detection, ultrasonic impulse-echo),
- microwaves (microwave tomography),
- magnetic fields (high-Tc superconducting magnetic sensor),
- electrical fields (ohmmapper),
- temperature fields (e.g. infrared thermography),
- gravitational fields,

- nuclear methods,

Most of these technologies are revisited below.

Data gathered from responses to the SON were compiled in a report [24]. The report covered the following providers:

- Bakhtar associates (GPR with narrow step-frequency bands and low power – see below)
- Ball Subterranean Systems (GPR to “see ahead” in Horizontal Directional Drilling)
- EIC/CTC/NASA (Acoustic Resonance with surface piezoelectric sensors – uses ambient vibrations)
- GSSI (GPR - see web site in Appendix B)
- GeoRadar (Stepped-FM GPR - see web site in Appendix B)
- John Hopkins University (Electrical Conductivity Object Locator, TerraHertz system – UXO detection, sensing of impressed currents in pipeline or tracer wire)
- NSA Engineering (Seismic Reflection Tomography to “see ahead” in tunnels)
- Penn State University / CRREL (GPR - see web site in Appendix B)
- SC&A Inc. (Magnetometer and Electromagnetic Induction – for UXO detection)
- Sequel Research Corp./ Ventus Inc. (Ultra narrow Advanced Impulse Radar)
- Computing Devices Canada (Electrical Impedance Tomography – not expected to work through asphalt and concrete)
- Sensors and Software (GPR - see web site in Appendix B)
- IDS, Italy (GPR- see web site in Appendix B)
- University of Cape Town, South Africa (GPR- see web site in Appendix B)

Below are some excerpts of the report summarizing the findings of the report:

> *None of the identified technologies is capable of providing a complete solution to the utility location problem. GPR is the most promising single area of technology development since it can identify nonconducting pipes and cables. There are severe limitations on depth penetration of signals in conducting soils, however.*
>
> *It is the author’s opinion that multisensor (e.g. GPR, plus acoustic, plus electromagnetic) and multifrequency approaches offer the greatest potential for stand-alone utility location in the future.*

It is believed that similar statements can be made about void detection: none of the technologies can provide a complete solution, but a combination of technologies, (e.g. visual, plus HWD, plus DCP) can provide a very successful assessment [1].

3.1.2.3. AASHTO

The American Association of State Highway and Transportation Officials has supported the development of a GPR system to locate maintenance problems in highway pavements, including: stripping in an asphalt layer, moisture in base layer, voids or loss of support under rigid pavements, and overlay delamination [25].

3.1.2.4. FAA

The Federal Aviation Administration (Technical Center) has, in the past, contracted to the U.S. Army Corps of Engineers (ERDC-WES, Geotechnical Branch) for their GPR needs (the FAA Technical Center does not own a GPR). Michel Hovan indicated that GPR is still considered more of a research tool than an operational system.

The FAA also sponsored research at ERDC-WES in 1989 [3] and 1993 [4] to look into nondestructive test equipment for airfield pavements, some of which is applicable to void detection. As a result of this research, the FAA purchased a HWD.

3.1.2.5. FHWA

The Federal Highway Administration has also worked with GPR. Glen Washer, FHWA, shared some of their experience with existing and upcoming GPR technology:

> *Existing GPR technology has been used to detect defects in airport pavements. The new Denver Airport, for example, was a project on which GPR was used to evaluate the pavement following construction. I believe that work was done by CTL, of Skokie, IL. There are also several vendors that market GPR services and equipment for this purpose, including GSSI and Penetradar.*
>
> *As you may be aware, we have been working for several years with the Lawrence Livermore National Laboratory on the development of a new type of ground penetrating radar system for the evaluation of concrete bridge decks. The system utilizes a 64 element array of radar antennae to evaluate bridge decks at highway speeds, and generate images of internal defects. The status of this research is that a prototype system has been developed and we are currently testing the system in the field. This field testing has indicated that the existing prototype will require improvement before it is fieldable as a reliable device for the detection of voids and delaminations in concrete, and we are currently in the process of developing a program to build a second generation of the system with the cooperation of State Departments of Transportation.*

The FHWA also provides support on using GPR on concrete bridge decks, measuring pavement thickness, or on borrowing the GPR van (see Appendix B).

3.1.2.6. LLNL

As indicated in the previous paragraph the Lawrence Livermore National Laboratory is developing a GPR for FHWA called the HERMES Bridge Inspector (see web address in Appendix B). This is an air-launched antenna system, with a 1 to 5 GHz micropower pulse radar. It can penetrate about 12 inches into concrete, and is used to detect corrosion of the reinforcing steel. It is expected to be operational at 55 mph on freeways. The system has an array of 64 antenna pairs for transmitting/receiving ultra-wideband pulses with a low noise to signal ratio. It provides a fast, large surface coverage.

The HERMES system is very expensive, but a smaller one – PERES (Precision Electromagnetic Roadway Evaluation System), and a portable one – PIRIS (Portable Impulse Radar Imaging System), are being developed. Although developed for reinforcement detection, the system can be upgraded to detect voids under pavements.

3.1.2.7. CALTRANS

The California Department of Transportation (CALTRANS) has only two employees in charge of GPR. Bill Owens, CALTRANS, indicated that they have a GPR system that is used occasionally when voids are found to determine their extent. No proactive void detection program exists.

3.1.2.8. NYSDOT

The New York State Department of Transportation (NYSDOT) has had some experience with GPR. However, only 25% success rate is claimed. Phil Walton, NYSDOT, shared some of that experience:

> *Ground penetrating radar, in our experience, has proven to be a useful tool for locating voids and some buried objects (the edges of concrete footings, for instance) beneath pavements. However, the technique has been successful on only about 25 % of the projects we have tried. Some of those where the equipment was unable to show voids were in areas of clayey soils that had a high moisture content, and we were not surprised when the survey failed to show the hoped for results. It was clear soon after the data was collected that it would not be beneficial to spend many hours reducing the data. In this situation, the contractor was paid for mobilizing, data collection, and several hours of data analysis on a pre-set fee schedule. Consequently, the Contractor received a fair payment for the work done, without taking all the risk for delivering results.*
>
> *On our most successful project, completed in 1993, the contractor Penetradar identified voids beneath concrete pavement that formed due to loss of fine sandy silt backfill material into a deteriorating corrugated metal pipe. The voids that were identified were subsequently drilled and grouted after temporary patches were wedged in place inside the pipe. This investigation used high frequency radar antennae for optimum resolution and relatively limited penetration. Each of the six lanes in this section of highway was surveyed for a distance of approximately one mile and 17 voids or suspected voids were found. This area continues to be a problem, however it is not known whether the current pavement distress is a result of old undiscovered voids or recent soil loss.*
>
> *Another successful project involved the locating of the limits of existing buried pile caps on an extensive viaduct structure in a city environment. The proposed widening and reconstruction of this structure necessitated an accurate knowledge of the size and*

*orientation of the existing pile caps. The Consultant on this project was EBASCO, and they used their own staff to perform the investigation. The survey started at a site where test pits could be excavated for purposes of verification. Once the operators were *calibrated* to the conditions, the survey commenced to areas where conditions were unknown. The results have not been field checked since the construction project was never funded, but the results seemed very reasonable, and certainly cost effective.*

On a 1987 project, again in an urban environment between 6th and 12th streets of Manhattan along the FDR Drive, ground penetrating radar was used in conjunction with a magnetometer survey, and an electromagnetic terrain conductivity investigation, to locate voids behind a sheet pile bulk head that was believed to be perforated due to corrosion. The combination of the techniques clearly indicated where voids had formed due to material loss through the sheeting. On this project, the sub-consultant used antennae in the 500 and 300 MHz range that are capable of penetrating up to several tens of feet in depth depending upon the dielectric properties of the resistive materials. It was primarily the GPR that provided the location of the voids, since the other methods could only provide information about the integrity of the steel sheeting. All this work was performed by Weston Geophysical of Westboro, MA.

In 1989, sections of the FDR Drive between 14th and 18th streets in Manhattan were surveyed for voids beneath the pavement. Approximately 16,800 lineal feet of scans were done with 1 GHz transducers and 4350 lineal feet of scans were done with a 500 MHz transducer. The surveys indicated many areas where the pavement showed significant thickness of overlay, implying past subsidence possibly related to void formation. Fifteen sites were selected for coring based on interpretation of the GPR data, but in only one case was a void found. It was theorized that the pavement had cracked, lost its structural strength and collapsed to rest on the soil. The depressions in the pavement were subsequently shimmed with asphalt and eventually overlaid. In their discussion of the results of the GPR survey, the sub-consultant Donohue and Associates indicated the 500 MHz transducer gave approximately the same depth penetration as the 1 GHz transducers due to severe signal attenuation resulting from the presence of high moisture content soils.

Sites where GPR was not effective are not so well documented. To name a few from memory:
1. High moisture content clayey soils attenuated signals and failed to locate known voids that had formed over utility installations.
2. No significant results were achieved when GPR was used to locate masonry box culverts on a very old state highway. The soil was silty and clayey in nature and contained a high moisture level.
3. At a site where soil conditions are sandy, some voids had developed over the drainage pipes in the area. It is uncertain whether no more voids exist, they are insignificant in size, or the survey did not detect them.
*4. During a demonstration in conjunction with FHWA, we tried to locate zones of seepage from a water filled canal. The thin concrete canal *floor* was constructed on jointed limestone. There may have been some valuable data collected, but the operators with their limited experience could not interpret it.*

3.1.2.9. FLORIDA DOT

The Florida DOT State Pavement Design Engineer, Bruce Dietrich, was contacted. The Florida Department of Transportation has one engineer, Jerry Moxley, in charge of GPR. He is in charge of determining the extent of recently discovered sinkholes. The DOT does not have a proactive program of sinkhole detection.

3.1.2.10. NAVAIR

NAVAIR was also contacted at NAS Patuxent River. Ignacio Perez indicated that most of their NDE is aircraft related but that some technologies, such as microwave, could perhaps be extended to void detection. He recommended contacting Robert deNale and John Liu at NSWCCD. Their response is included later under microwave and millimeter wave technology.

Ignacio Perez also provided some information on an SBIR on Nondestructive Technology Review and Experimental Plan for Concrete Deterioration. Covered technologies, such as Impact-Echo, are detailed later.

3.1.2.11. NRL

The Naval Research Laboratory was also contacted, about GPR and related technologies. Richard Mignona shared his insights on GPR, microwave and low frequency ultrasound (LFUT). The latter two are detailed below.

3.1.2.12. U.S. AIR FORCE

The U.S. Air Force Research Laboratory, Air Base Technology Branch (AFRL-MLQC), has successfully used a GPR for locating voids at several military installations [1, 8] (Figure 13). This GPR is often used in conjunction with a Heavy-Weight Deflectometer (HWD) and an Electronic Cone Penetrometer (ECP) from AFCESA. Their detection success is in part based on the fact that all 3 technologies are often used together.

3.1.2.13. U.S. ARMY

The U.S. Army, ERDC, Waterways Experiment Station, Geotechnical Branch, Vicksburg, MS, has a GPR that they have used successfully to detect pavement thickness, base thickness and utilities. It was developed under a Small Business Innovative Research (SBIR) contract to Pulse Radar (Houston, TX), and is a multi-antenna system (100, 250, 500 and 1000 MHz antennas) (Figure 13).

3.1.2.14. NULCA

The National Utility Locating Contractors Association (NULCA) is one of the sponsors of the yearly Damage Prevention Convention (http://www.underspace.com/nu/index.htm). Some of the technologies used for detecting utilities underground could be extended to cover void detection. The only one that appears suitable for both applications so far is GPR, which was covered extensively at the last Damage Prevention Convention (Dec. 1999, Long Beach, CA).

3.1.2.15. BAKHTAR RADAR

A recent article in Jane's Defence Weekly (22 December 1999) indicated the Bakhtar radar as a "breakthrough" that could help DoD "see" underground. This system was developed under funding by the Air Force, Eglin AFB, FL. This system uses relatively narrow frequency bands of GPR pulses, and stepped frequencies, to get a better signal to noise ratio. This system also uses a low incident power of 0.1 Watt, and enhanced post-processing software for reflective tomography imaging [20].

3.1.2.16. OTHER GPR SOURCES

In most applications, the GPR is used as an analysis tool, not a proactive tool, i.e. it is used to further define the extents of a void once one is suspected or found [26]. Even then, the analysis can be difficult. For example, personnel from the Department of Geological Sciences at Cornell University had trouble finding known 12-foot deep caverns just 6 feet under the surface [27].

3.1.3. GPR CONFERENCES

3.1.3.1. GPR 2000

The upcoming conference GPR 2000 will be held in Australia, 23-26 May 2000. More information can be obtained at http://www.cssip.uq.edu.au/~gpr2000/gpr2000.html.

3.1.3.2. INTERNATIONAL UWB CONFERENCE

The Ultra Wideband Working Group recently hosted the 1999 International UWB Conference. The event was held on September 28 - 30, 1999, in Washington, DC at the Crowne Plaza/ Sphinx Club (http://www.uwb.org/index.htm). The Ultra Wideband Working Group (UWBWG) has been founded in response to interest voiced by the UWB Community at the UWB Communications Workshop on May 25-27, 1998, as well as a result of the FCC's NOI (Notice of Inquiry) on UWB for radio and radar systems.

3.1.3.3. UXO/COUNTERMINE FORUM

This conference will be held 2-4 May 2000 in Anaheim, CA, and can be accessed at http://www.denix.osd.mil/denix/Public/News/UXOCOE/Conference/conferences.html.

3.1.3.4. IEEE RADAR 2000

This conference will be held 7-11 May 2000 in Washington, D.C. and can be accessed at http://www.ewh.ieee.org/soc/aess/radar2000/summary.htm.

3.1.3.5. DAMAGE PREVENTION CONVENTION 2000

The next Damage Prevention Convention will be held 29 November to 1 December 2000 at the Bayside Exposition and Conference Center, Boston, MA. Information on this and the 1999 convention can be found at http://www.damageprevention.com/.

3.1.3.6. SAGEEP 2001

The next Symposium on the Application of Geophysics to Engineering and Environmental Problems will be held 4-7 March 2001 at the Doubletree Hotel, Denver, CO (http://www.sageep.com/). It is organized by the Environmental and Engineering Geophysical Society (EEGS), and covers GPR and seismic methods, among others.

3.2. MICROWAVE AND MILLIMETER WAVE TECHNOLOGY

The Naval Surface Warfare Center, Carderock Division (NSWCCD) has used microwave and millimeter wave technology to detect and size defects in Navy fiber reinforced composites used in ship structures, under support from ONR and NAVSEA. Both technologies have been tested successfully against embedded artificial defects, as indicated by John Liu, the Principal Investigator. These defects can be as small as 3/8-inch in diameter, usually requiring frequencies in excess of 12 GHz (frequencies for millimeter waves are often considered at least in excess of 30 GHz, e.g. http://www.mmwrpt.com/). However, the penetration of these waves is small (inches only). As indicated by John Liu:

> *There are no fundamental difference in the physics of GRP and microwave technology as both are based on the propagation and scattering of electromagnetic waves. Of course, the details of the equipment used are somewhat different.*

Hence these two technologies were not pursued further.

3.3. INFRARED THERMOGRAPHY

Infrared thermography has been used for a number of years to find superficial delaminations in pavements at speeds of up to 10 miles per hour [14]. This technique relies on the fact that the thermal conductivity of a pavement is affected by cracks, superficial delaminations, sandy concrete, etc… Hence during daylight hours, the pavement surface above these voids will exhibit higher temperatures (and cooler patterns at night). The readings are affected by solar radiation, cloud cover, ambient temperature, wind speed and surface moisture. However, once these factors are accounted for, the temperature differential between sound concrete and concrete with superficial voids can be bounded (typically within less than 5ºC) and measured (with a sensitivity of 0.1ºC). This technique has typically been applied to detect shallow delaminations and voids in pavements, but has also been extended to find underground pipeline leaks and voids under pavements [28]. The concept is that relatively shallow underground heat sources or sinks generate a temperature differential field that will leave a surface signature. This surface signature can then be sensed by infrared thermography. As indicated in [5], "… deeper cavities often show signs of their presence in the near surface and can be detected in shallow geophysical data."

3.4. MAGNETIC FIELDS

The magnetometry method is based on detecting anomalies in the earth's magnetic field. When ferrous material, such as a steel culvert, is placed within the earth's magnetic field, it develops an induced magnetic field. The induced field is superimposed on the earth's field at that location creating a magnetic anomaly. By measuring simultaneously at two elevations and by using two sensors separated by a fixed distance these anomalies can be detected by using a magnetometer. The difference in the magnetic intensity between the two sensors divided by the distance between them develops the vertical gradient, hence magnetic contour maps, which are analyzed to determine the depth of the ferrous material.

The second and most common use of magnetics uses direct magnetic induction and may be coupled with magnetometry and radio frequency tracking. In direct magnetic induction, a signal is induced by direct coupling. The location of the ferrous material is then detected with the receiving antenna by either peak or null mode of operation. The depth and location of the ferrous object is determined by triangulation.

Direct magnetic induction devices are basically tracing tools for metallic pipes and cables because the operator must initially induce a signal in each line so that detection and tracing could be accomplished from the ground surface [17]. Magnetometers can only be used to detect ferrous metal objects or bedrock features with contrasting magnetic content [29]. This technology was perceived to be of limited application for void detection.

3.5. ELECTRICAL RESISTIVITY AND CONDUCTIVITY

The electrical resistivity method is typically used to characterize vertical (sounding) and lateral (profiling) changes in subsurface electrical properties, allowing for 3-D mapping. Traditionally, an electrical current is introduced directly into the earth by hammering probes (electrodes) into the ground at predetermined distances. The resulting voltage difference between another pair of electrodes is measured and the subsurface resistivity calculated. Resistivity is the reciprocal of conductivity, therefore measuring resistivity provides information on subsurface conductivity [29].

The OhmMapper, a recent development from Geometrics, is a capacitively coupled resistivity system designed to measure subsurface resistivity in areas with high surface resistivity. This system uses an alternating current with a particular frequency induced in the earth by alternating voltage applied to the transmitting dipole and the alternative voltage induced in the receiver's dipole is measured. The measured voltage will be proportional to the resistivity of the earth separating the two dipoles and the current delivered to the transmitter dipole.

Resistivity or conductivity mapping can also be completed using airborne electromagnetic data, with high rates of data acquisition [30, 31].

These methods are similar with the GPR in terms of being dependent on the soil electric conductivity. Objects or areas in the ground with different electrical properties will transmit differently, and appear as anomalies. Soil penetration (measured voltage) depends on soil type and moisture. Soil moisture, for instance, will quickly decrease and limit this method's performance (i.e. dry sandy soils are best). Conductive environments are the principal limiting factor for depth investigation.

As with the GPR systems, real time soil cross sections can be obtained for immediate analysis, or they can be stored for later evaluation. The raw signal can also be postprocessed to better identify anomalies. In any case, proper interpretation of electrical output requires considerable operator experience and is an art as well as a science. Hence, with limitations similar to GPRs, but being more sensitive relative to water and soil electrical conductivity, this technology was not pursued further.

3.6. SPONTANEOUS POTENTIAL

Spontaneous potential mapping measures the natural voltage that exists at the ground surface [5]. Measurements are completed between two non-polarizing electrodes in contact with the ground. This technique can detect a concentrated source of natural electrical current of the type typically associated with concentrated downward infiltration of water, i.e. related to a sinkhole. However, this technique is more appropriate for detection of seepage from dams and embankments, or other subsurface water movement [5].

3.7. VISUAL INSPECTIONS

Last but not least, visual inspections fall within these electromagnetic techniques, since the visible spectrum (4. 10^{14} – 7.5 10^{14} Hz) can be used to detect pavement problems for the surface. Visual inspection of the airfield pavements should be performed on a frequent basis by local airfield personnel to locate potential problem areas. Such inspections should monitor pavements for conditions that may affect aircraft movement (FOD, depressions, pavement deterioration, etc…). Frequency should be determined by local physical conditions and operational tempo as to minimize the hazards. In flexible (asphalt) pavements, depressions are evident after a rainfall, or by the concentric marks left by the evaporated water (Figure 4). In rigid pavements, standard 12½ by 15-ft concrete slabs cracked into two or more pieces, as well as slabs that exhibit faulting at joints, may indicate underlying soft spots or voids. In particular, areas above drainpipe crossings should be carefully inspected since most problems appear near these pipes. Problems observed in unpaved areas above a pipe are early warning signs of problems in nearby paved areas above the same pipe. Depressed pavement or shattered slabs surrounding drainage structures (catch basins) indicate infiltration of soil materials into the structure or pipe. Visual inspections can also follow PCI (Pavement Condition Index) guidelines, as detailed in NAVFAC MO-102 Manuals, and as detailed in ASTM Standards (ASTM D 4694) [32]. Visual inspections by experienced pavement engineers can detect up to 50% of voids under concrete slabs [33].

3.8. SUMMARY OF ELECTROMAGNETIC TECHNIQUES

The first tool in void detection should be visual inspection. Although some surface failures can be obvious (Figures 1 and 4), other visual indications of potential problems, or even imminent failure, can only be picked up by trained personnel. PCI (Pavement Condition Index) assessments are routinely conducted at all Navy and Marine Corps airfields, every 3 years or so, by trained personnel that are also qualified to search for signals of potential void problems. Specific detection guidelines were included above and are repeated in Appendix A.

From the other available electromagnetic technologies, it appears that GPR and possibly Infrared Thermography are the most promising at this point. However, it seems that in general both technologies are not mature enough for the specific application of void detection. GPR is still considered more of a research tool than an operational tool, and its success rate in finding voids, or areas of loose soil under pavements, is somewhere between 25% and 75%. This matches previous NFESC experience at NAS Pensacola [1], where the GPR only located 4 out of 11 known weak areas.

The GPR, however, has other advantages that make it a useful complementary tool. In the structural assessment of the pavement, knowledge of the pavement thickness is very important, and GPR can be very useful in getting an average thickness over the area of interest This is a task routinely completed by GPR [34]. Also, many of the void problems originate near drain pipes, and the GPR can be very helpful in determining the actual location of the pipes. Finally, once a void has been found, GPR can be used to determine the void's extent.

In some cases, for example if the area to investigate is very significant, using the HWD to perform a thorough coverage may not be possible. In that case, it is recommended that: (1) the HWD be used at any critical location within the area of concern, (2) the GPR be used to complete coverage of the area (assuming the soil characteristics allow its use), (3) the HWD be used again at the discrete locations where the GPR found anomalies, and (4) DCP testing be completed where weaknesses were confirmed by the HWD.

It is recommended that both the GPR and Infrared Thermography be further investigated and developed, in an attempt to improve their reliability in detecting voids. It is also recommended that a small portable GPR with an antenna of about 500 Hz be acquired to facilitate the field work of the pavement team.

4. TRANSIENT LOAD TECHNIQUES FOR VOID DETECTION

4.1. SEISMIC WAVES

Refraction [5], reflection [5], and propagation [35] of seismic waves can be used to detect subsurface anomalies, such as voids or areas of weak or loose materials. These methods often require lengthy field testing and complex data manipulation [36], although some simplifications in field testing have been reported [37]. In some cases, seismic refraction can outperform GPR, e.g. in the case of clay-rich soils [38].

A cross-hole seismic survey can be performed to detect subsurface anomalies [35]. The detection is based on the effect of the anomalies on the velocity of the seismic waves. This system was used by the Florida Department of Environmental Protection to assess the extent of a 185 feet deep and 120 feet wide sinkhole that formed at an industrial plant in Florida [39]. While appropriate for this application, the system seems too cumbersome for airfield pavements.

The FHWA has a Seismic Pavement Analyzer (SPA), developed under the Strategic Highway Research Program (SHRP) (http://www.ota.fhwa.dot.gov/tech/pave/te21.html). This system uses the Seismic Analysis of Surface Waves (SASW) method [40] to measure pavement thickness, overlay bond, and pavement layer moduli. Test and evaluations of SPA were conducted in the states of Florida and Texas in 1998 [41, 42, 43], and a portable version (PSPA) was developed. One of the shortcomings of using the SPA in the time history mode is that is induces deflection basins two orders of magnitude smaller than the HWD, resulting in higher relative errors. Whether in the time history or the frequency response function mode, there was difficulty in correlating the SPA results to the FWD results [43]. The A&M Florida State University College of Engineering constructed test sections inside the school compound to serve as calibration sites. Problems encountered during testing and implementation indicated that further development is still required. This conclusion was also supported by the Texas team [42] and others [44].

The U.S. Army Corps of Engineers, ERDC-WES, has also used seismic waves to analyze pavements, but their technology was mostly directly at determining concrete pavement characteristics, not void detection. They also developed a portable seismic pavement analyzer (PSPA) that uses ultrasonic surface waves to determine pavement flexural strength and modulus.

4.2. IMPACT-ECHO

The impact-echo system was developed in the mid-1980's by Professors Mary Sansalone (http://www.cee.cornell.edu/fac/Sansalone.htm) and Nicholas Carino [45]. This instrument is available commercially (e.g. under the name of DOCter Impact-Echo Test System http://www.germann.org/products/docter.htm, or http://www.impact-echo.com/index.htm). It has been used at NFESC to find flaws in concrete slabs. As explained below, this system uses seismic waves for detection.

> *A short-duration stress pulse (15 to 80 microseconds) is introduced into the object by mechanical impact using a small steel ball, diameters range from 2-15 mm. Three types of waves are generated by the impact, a surface R-wave (Raleigh wave), a P-wave (Primary wave) and an S-wave (Secondary wave). The last two travel into the test object.*
>
> *{PRIVATE}The R-wave propagates on the surface in a circular pattern similar to that of a stone dropped in water, and will not return unless there are edges to generate reflections. For a proper wavelength, determined by the size of the impactor, the P-wave an S-wave will be reflected when they reach a material with another acoustic impedance, such as air, and return to the surface, be reflected again, etc.*
>
> *The P-wave will, upon returning to the impact point, cause a displacement of the surface. The S-wave will, in the vicinity of the impact point, have its lowest amplitude upon reflection, contributing only minimally to the surface displacement. So, if the transducer sensing the displacement of the surface is positioned close to the impact point, only the R-wave and the successive arrivals from the reflections of the P-wave will be detected.*

The system has typically been used for plat-like structures (bridge decks, floor slabs, pavements, and walls) that are 20 inches or less in thickness. Flaws with lateral dimensions of at least one-half the flaw depth can be detected. This system is therefore very useful to detect flaw or discontinuities in a single continuum, and has been very successfully used for the following applications:

- measurement of thickness, e.g. of asphalt overlays, roads and pavements
- location of cracks, voids and honeycombing
- depth of surface opening cracks
- delamination surveys of slabs, shotcrete, tunnel lining elements, cooling towers, etc.
- integrity testing of a protective membrane below an asphalt overlay
- debonding between reinforcement and concrete, e.g. caused by corrosion
- porosity between two layers or lack of bonding
- presence of air in injected cable ducts
- evaluation of ASR and freeze-thaw attacks
- evaluation of the depth of surface opening cracks
- evaluation of early age strength development of maturing concrete.

The system appears to have potential application to the detection of voids under pavements [46], although it has not been used that way [47].

4.3. HEAVY WEIGHT DEFLECTOMETER

This technology was successfully demonstrated by NFESC and SOUTHDIV [1]. The heavy weight deflectometer was able to detect all voids or loose soil areas near drainpipes at NAS Pensacola. Void detection using a GPR at the same locations proved disappointing, detecting only 4 areas out of 11 found with the HWD. The methodology is described in reference [1], which can be found, together with additional documentation, at the NFESC web site http://intranet.nfesc.navy.mil/apvdt.htm. Some excerpts are reproduced below for easy reference.

The HWD, or Falling Weight Deflectometer (FWD), is an impact load device, which applies a single-pulse transient load of about 20 to 30 milliseconds of duration [3, 4, 6]. This trailer mounted device applies a dynamic force to the pavement surface by dropping a weight onto a set of rubber cushions which in turn transfer the load to the pavement through a 17.7-inch diameter plate. The drop height can be varied from 0 to 15.7 inches to produce forces from 9,000 to 60,000 lbf. Load is measured with a load cell at the center of the plate. Typically seven velocity gages are used to measure pavement velocities and determine corresponding deflections. These deflection gages (D1 through D7) are located at 0, 15, 24, 36, 48, 60, and 72 inches from the load point to get the deflection basin.

4.3.1. HWD ADVANTAGES

The advantage of this method is that the results can be directly related to a load carrying capacity for the pavement [48]. The disadvantage of the method is that tests can only be completed at a limited number of discrete locations, and each test covers only an area about 5 feet in radius, or less. Hence in the search for voids or pavement weaknesses, tests must be conducted on 10 ft grids, which becomes very labor intensive. Any weakness more than 5 ft from the grid will not be detected. Finally, a secondary testing method, such as ECP (electronic cone penetrometer), DCP (dynamic cone penetrometer), or SPT (standard penetration test) must be used to further pinpoint the origin of the weakness and its depth.

4.3.2. HWD PREDICTION METHODOLOGY

The following procedure using the heavy weight deflectometer was developed by NFESC for void detection in limited areas. From 5 to 14 October 1999, NDT data was taken at NAS Pensacola using NAVFACENGCOM Southern Division HWD [1]. The data collection procedure was as follows:

- Follow each drain pipe and test every 10 feet (line 1)
- Follow each pipe every 10 ft again but offset to right by 10 ft (line 2)
- Follow each pipe again but offset to left by 10 ft (line 3)

Hence, three sets of readings are obtained for each distance along the pipe. The 10 feet distance was chosen because it is expected that the HWD cannot sense pavement deficiencies beyond a 5 feet radius.

At each location a set of seven deflections is obtained, D1 though D7, where D1 is under the load point, and D2 through D7 are at 15, 24, 26, 48, 60 and 72 inches from D1, respectively.

Once the data was gathered, the impact stiffness modulus (ISM) could be used to assess the pavement relative strength at each drop location. The ISM reflects the local pavement stiffness under the load point, and is found by dividing the load by D1. This ISM is calculated with the LEEP program [1].

Similarly, the load can be divided by the other deflections, to give ISM2 = Load/D2, and so on up to ISM7 = Load/D7 (ISM1 would be the original ISM). This is of interest since D1 usually reflects the state of the pavement itself, whereas D7 reflects the state of the subgrade. Using D1 alone is not sufficient to successfully detect voids under the pavement. The deflection data for each feature is easily accessed via the file *feature.bas* created after BASIN is run. The ISM1 through ISM7 plots along the drainpipes can be plotted and analyzed. They can also be normalized (by dividing each plot by the highest value in the plot) to determine relative effects of pavement weaknesses on each sensor.

Once the plots are completed, the following rules can be followed to determine potentially weak areas:

- An absolute ISM value below 500 kips/in is of concern
- A relative ISM decay indicates an unexpected weakness
- A weakness in ISM 1 indicates it is shallow
- A weakness in ISM 7 indicates it is deep (3 to 20 feet)
- A weakness in both ISM 1 and ISM 7 indicates a general lack of support

These guidelines have proven very successful in determining voids and weak or loose soils under pavements using the HWD [1]. Other void detection methodologies using the HWD have been attempted [12, 49, 50], but they either are more complex or do not appear as reliable.

4.4. ROLLING DEFLECTOMETERS

The rolling weight deflectometer (RWD) is similar to the HWD in that a load is applied to the pavement and a deflection basin is sought. However, with the RWD the transient load is applied by a continuously rolling wheel, and the deflections are measured with non-contact laser gages [51]. The first RWD was developed in the mid-1970's but had deflection measurement problems and did not prove practical [51]. Current RWD versions can gather load and deflection data while traveling at 20 mph [51]. One shortcoming with the RWD is that it currently only measures one deflection near the load. This may prevent the detection of deeper voids (usually detected with the D7 sensor). However, this shortcoming should be easy to address. Another difficulty resides in obtaining the instantaneous deflection basin around the load. If these problems are resolved, the RWD holds great potential for void detection due to its high data acquisition rate.

A rolling deflection meter, similar to the RWD, was also developed in Sweden, which is expected to be capable of performing measurements at up to 40 mph [52, 53].

The second-generation high-speed deflectograph (HSD) [53] is also a similar vehicle, except that it uses laser Doppler sensors to measure the pavement velocity. From this velocity, the pavement deflection can be derived. This is different from the RWD, which measures the deflection directly, and appears less complicated. This deflectograph is expected to be operational in 2001 and reach speeds of up to 45 mph.

4.5. VIBRATORY LOADING SYSTEMS

Some systems can input a vibratory load to the pavement, and use geophones to measure deflection [2, 3, 4]. The vertical input load is generated by two eccentric masses, or via a hydraulic system. A static load is preimposed on the system to insure contact during cyclic loading. The cyclic load is typically sinusoidal, from 1,000 to 30,000 lbs peak to peak, and with frequency from 5 to 100 Hz. In some systems the load and frequency are fixed, but in others they can be varied. In the early systems, the cyclic load was low, i.e. very different from the aircraft loads they were simulating, and introducing relatively higher error in the data. These vibratory loading systems are very similar to the HWD or FWD, but not as popular. A comparison between vibratory and static deflectometer systems can be found in [2, 3, 4].

4.6. ROLLING DYNAMIC DEFLECTOMETER

In the same way the RWD evolved from the HWD, the Rolling Dynamic Deflectometer (RDD) has evolved from the static vibratory systems. The RDD can input a vertical cyclic load on the pavement and gather vertical deflections, while traveling along the pavement at speeds around 1 mph [54, 55]. This system can provide a fast, quasi-continuous reading, i.e. it can provide an efficient way of insuring that no local deficiencies are missed. At the present time, efforts have been directed at measuring deflection basins, not backcalculating deflection moduli. While this may complicate the determination of the pavement load-carrying capacity, the current capabilities are sufficient to quickly determine relative pavement weaknesses and approximate depth. These capabilities make the RDD a very promising technology for void detection.

4.7. ULTRASOUND

Current pulse-echo ultrasound scanners are used in medical applications to provide high quality images of internal organs. They operate by transmitting pulses of sound into the tissue. Echoes of the pulses are displayed as dots on a screen. Imaging is done by sweeping the pulsed beam through the region to be scanned, and detecting and displaying echoes from objects in the sound path.

Sonic and ultrasonic methods have also been applied for non-destructive testing of concrete [56, 57, 58]. These methods (e.g. Ultrasonic Pulse Velocity, Spectral Analysis of Surface Waves, and SuperScanner) use seismic waves (compression, shear and surface waves) to characterize layered elastic media. This methodology is similar to the Impact-Echo, and is directed at characterizing slabs or pavements.

Ultrasonic methodology is marred by the physical (fluid) coupling of a transducer to the test media. Based upon high transduction piezoelectric transducers, Second Wave Systems (http://www.secondwavesystems.com/) has a non-contact ultrasonic analyzer which can be applied to ceramics, metals, polymers, and particulate and fibrous composites for the measurement of thickness, density, velocity, defects, microstructure, mechanical properties, and imaging. After routine calibration, these tasks are performed automatically under ambient environment without any contact with the test medium. This technique is currently limited to small laboratory size samples (e.g. 8-mm thick aluminum sample).

4.8. ACOUSTIC REFLECTION SOUNDING AND ACOUSTIC EMISSION

Acoustic reflection methods are not commonly used in subterranean situations because of the substantial attenuation of the high frequency acoustical signals in porous and fractured materials. In addition, the amplitude of the reflected signal depends mainly on the difference in elastic wave velocity and density of the contacting materials, as well as the geometry of the reflecting surfaces. High frequency acoustic reflection sounding has proven to be an effective means to study salt rock mass structures due to the relatively low attenuation of the signal through the rock. In this case, acoustic reflection sounding was claimed to be capable of a greater depth of penetration than ground penetrating radar, and a better level of resolution than seismic methods [59]. It is not clear how successful this technique would be for void detection.

Acoustic emission detection from sinkhole void formation was also attempted at the Capital City Airport [15], although this later proved not too successful.

4.9. AUDIBLE ACOUSTIC REFLECTION SOUNDING

Part of the acoustic spectrum includes audible stress waves. Techniques exist that use audible sounding to detect delaminations in concrete slabs. One of them is the standard practice for measuring delaminations in concrete bridge decks by sounding [60]. The method covers two procedures, (A) electro-mechanical sounding with a tapping device, sonic receiver, and recorder, and (B) chain dragging or hammer tapping, with the operator serving as sonic receiver and recorder. While this method is typically used to detect delaminations, it could feasibly be extended to detect voids right under the pavement.

4.10. SUMMARY OF TRANSIENT LOAD TECHNIQUES

Within the transient load techniques addressed, the HWD was shown to be very reliable in detecting weaknesses under pavements. NAVFAC currently owns several standard deflectometers, 3 under the pavement program (located at three Engineering Field Divisions), and one at NFESC under the structures program. The pavement group currently performs structural evaluations at all airfields about once every 8 years, and has trained personnel to complete these evaluations in-house. Tri-Service support is also available from the Army (ERDC-WES) and the Air Force (AFCESA), who also own deflectometers. All three services have cooperated in the successful void detection effort at NAS Pensacola [1], and all are qualified to perform void detection assessments. It is recommended that the HWD be considered a primary tool in detecting voids in limited areas (e.g. near drain pipes).

The RWD is still in the development stage, but has the potential to accelerate data acquisition and processing compared to the HWD. Further investigation into the RWD is recommended.

5. OTHER TECHNIQUES FOR VOID DETECTION

5.1. VIDEO TAPING

Video taping the interior of drain pipes under airfield pavements can help pinpoint the location of potential problem areas. Leaks in the pipes, or at pipe joints, indicate suspicious locations. Accumulations of fines near the leaks are a good indicator of a loss of subgrade material, and possibly subgrade strength. In some cases, joint and pipe breaks, and even actual voids beyond them have been be observed [1]. However, it has been shown that this method may not identify all weak pavement areas [1], and it cannot determine the loss of load carrying capacity at the identified locations.

5.2. SOIL PENETRATION TECHNIQUES

Various techniques exist whereby rods with a conical tip are pushed or pounded into the subgrade to determine the subgrade bearing strength at various depths. These are destructive techniques, since they require drilling or coring through the pavement to reach the base and subgrade. The advantages of these techniques are that they can provide an independent verification of the existence of a subgrade weakness or void, they can also indicate the relative strength loss, and finally the depth and vertical extent of the weakness.

Three soil penetration techniques in particular are identified below:

- The Standard Penetration Test (SPT), also called Split-Spoon test because of the split-barrel used for soil sampling. This test is covered in ASTM D 1586 [61]. It consists in driving a split-barrel sampler to both obtain a representative soil sample and a measure of the soil resistance to penetration. The sampler is driven by dropping a 140-lb mass from a 30-inch height. The sampler is driven at 6-inch increments into the ground. For each increment the number of blows is recorded and is assumed to be representative of the soil strength.
- The Electronic Cone Penetrometer (ECP), in which the rod is pushed at constant velocity into the soil and readings of the resistance to penetration. AFCESA owns a truck-mounted ECP that they routinely use in their pavement evaluations [1, 8]. This system can perform quick evaluations down to 8 feet or more, but requires additional personnel. The AFCESA team typically has 4 operators, 2 for the ECP and 2 for the HWD, but can perform very fast and very complete evaluations.
- The Dynamic Cone Penetrometer (DCP), in which the rod is pounded down using a calibrated weight dropped from a constant height [62, 63, 64]. This system is portable, and its most recent version only needs a single operator. This system is designed to reach a depth

of only 4 feet, but in testing weak areas for voids, it is possible to further extend this testing depth. It is recommended that each Navy pavement team obtain a DCP.

Either the SPT, ECP or DCP are considered primary tools in the verification and determination of the void's depth and vertical extent.

5.3. QUASI-STATIC LOAD-DEFLECTION DEVICES

The plate bearing test is perhaps the simplest and best known such test. However, this test is not currently used due mostly to the time and heavy reaction equipment required, the difficulty in setting up a reference bar, and the limited amount of information obtained [2]. Others testing devices include the Benkelman Beam, the Curvature Meter, the LaCroix Deflectograph, the British Pavement Deflection Data Logging Machine, the California Traveling Deflectometer, and the CEBTP Curviameter, all described in [2]. The operation of these devices is too time consuming and they would not be practical for void detection.

5.4. GRAVITATIONAL TECHNIQUES

Gravity measurements can detect changes in the earth's gravitational field due to changes in subgrade density [5]. Microgravity measurements can sense very small gravity variations and detect underground voids. However, accurate gravity measurements are slow and difficult to make [65-67]. They require very accurate elevation measurements (within 3 mm). Extensive corrections must also be applied to gravity data before it can be interpreted [5]. Some authors have concluded that this method cannot reliably identify void locations [68]. This technique is not believed to be practical for void detection over significant areas.

5.5. SUMMARY OF OTHER TECHNIQUES

It is recommended that DCP (or ECP or SPT) testing be completed at all locations where HWD readings indicate the potential for voids or weak areas. Video taping can provide a complementary verification of the problem, and perhaps pinpoint the cause for the problem. In any case, video taping can give an assessment of the pipe status and its need for repair or maintenance.

6. RELATED TOPICS

6.1. VOID FORMATION

To reduce the expense of void detection, it is of interest to determine the areas of most problem potential and either limit or emphasize the evaluation to these areas. Knowledge of void formation is of interest to define where these areas might be.

6.1.1. DRAIN PIPES

One of the main causes in the formation of voids is a leaking drain pipe [1]. If the water table is above the pipe, and if the leak is severe enough, fines from adjacent soils can be eroded and transported into the pipe, and washed away. Over time this creates a void near the pipe that grows vertically as the top soil falls down. Once the void grows near the surface, a sinkhole eventually appears on the pavement. The "void" can be an actual void, or a volume filled with loose soil. Most observed sinkhole problems occur near drain pipes, and void detection should pay close attention to these areas [1].

Prevention of drain pipe problems includes pipe maintenance, inspection and repair.

6.1.2. KARST FEATURES

Karstic cavities form in areas of carbonate rocks [69]. Carbonic acid, from atmospheric carbon dioxide and rainwater, can dissolve the carbonate rocks and result in cavity or cavern formation. Eventually the cavity roof may collapse, resulting in a sinkhole at the surface.

Prevention of karst feature problems under pavements includes pavement crack sealing and joint seal maintenance to prevent rainwater from percolating under the pavements.

6.2. DATA FUSION

Data fusion seeks to integrate information from as many sources as possible to produce the most comprehensive and specific data about an entity, in this case the pavement and subgrade [2]. For void detection, it is apparent that several complementary techniques are needed to obtain the most reliable detection results. For example, HWD readings can provide a rough estimate of the depth a weak spot, but DCP can pinpoint the vertical location accurately. Rather than actual data fusion, an optimal set of complementary techniques is sought, such as the one described in [1].

7. CONCLUSIONS AND RECOMMENDATIONS

A review of airfield pavement failures was conducted for the Navy, Army and Air Force, and several accidents were found where aircraft had punched through pavements. Other Navy pavement failures were reported, which fortunately did not involve any aircraft, although some of them happened in active airfield pavements. Finally some commercial failures were also reviewed.

Since many failures are known to have resulted from subsurface voids caused by soil erosion near drain pipes, a survey was conducted of all Navy and Marine Corps airfields in an attempt to quantify the magnitude of the potential problem. On average, the airfields surveyed have about 15 drainage structures crossing under airfield pavements, compared to 33 drainage structures for NAS Pensacola.

A review of the state-of-the-art non-destructive technologies applicable to void detection under airfield pavements was also completed. Several electromagnetic and transient-load techniques were addressed. The experience of several Government agencies, State Departments of Transportation, academia, and private firms on all available applicable techniques was gathered and summarized. The following are conclusions derived from their shared knowledge:

1. No single technique is currently capable of providing a complete solution to the void detection problem.
2. A combination of technologies can, however, provide a cost-effective, reliable methodology to minimize the potential for accidental airfield pavement failure due to subsurface voids.
3. The optimum technology combination at the current time is a combination of visual, HWD and DCP techniques, which can be completed by a single operator. The DCP can be replaced by ECP or SPT, but these techniques require additional manpower.
4. Complementary technologies include video taping and GPR. Video taping was shown to allow for the detection of pipe failures indicative of potential void problems, and even the detection of actual voids. GPR is very useful for determining pavement layer thickness (for use in HWD structural evaluation), and location of drain pipes (assuming favorable low conductivity subgrade characteristics).
5. Promising technologies include RWD, HSD, RDD, GPR, and Infrared Thermography. It is currently not recommended to use these technologies as primary detection tools, but further development may increase their reliability for such application.
6. In some cases, e.g. when the area to investigate is very significant, using the HWD to perform a thorough coverage may not be possible. In that case, it is recommended that: (1) the HWD be used at any critical location within the area of concern, (2) the GPR be used to complete coverage of the area in an attempt to identify subsurface anomalies (assuming soil characteristics allow its use), (3) the HWD be used again at the discrete locations where the GPR identifies anomalies, and (4) DCP testing be completed where weaknesses were confirmed by the HWD.

This document further supports considering the HWD as a primary tool in detecting voids and determining the effect of the voids on the pavement load carrying capacity. It is recommended that a void detection survey be performed on the same cycle as the structural evaluation (every 8 years), and by a member of the Tri-Service Airfield Pavement Team until the technology is further disseminated.

It is also recommended that a DCP and a small portable GPR be purchased for further evaluation by NFESC. If successful, these two devices should be made available to all three EFDs performing structural evaluations.

8. ACKNOWLEDGMENTS

Funding for this research was provided by NAFVAC HQ (Public Works / Chakrabarti), and the NFESC DEMVAL program. The support of all the sources mentioned is gratefully acknowledged.

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MCAS Camp Pendleton Runway Failure

22 March 2000

- 6’ diameter by 4’ deep sinkhole
- on runway
- no aircraft involved

- Feature R3-1, NW edge, between TWA and TWB
- 1999 PCI = 79
- 1993 PCN = 47/F/C/W/T
- no utility line
- sinkhole due to water table variation (between -2 to -7 feet)

FIGURE 1. PAVEMENT FAILURE AT MCAS CAMP PENDLETON

NAS Pensacola Taxiway Failure

20 May 1999

- T-34C Turbomentor
- 4” AC

- TWA3 (LT2/3 @RW25R to25L)
- Nose gear sunk 12 inches
- 1999 PCI = 57 (high SCI)
- 1999 PCN = 48/F/B/W/T
- T-34C ACN = 3 to 5
- Pipe leak

FIGURE 2. PAVEMENT FAILURE AT NAS PENSACOLA

OLF San Nicolas Island Apron Failure

March 1998

- F-4 Phantom II
- 2”+2.5” AC

- Feature PA1-2
- 1992 PCI = 59
- 1994 PCN = 12/F/C/Y/T
- F-4 ACN = 15 to 24
- Base washed out

FIGURE 3. PAVEMENT FAILURE AT OLF SAN NICOLAS

<u>OLF San Nicolas Island Sinkholes</u>

March 1998

Sinkhole in Runway R12-1B

Sinkhole near Runway

FIGURE 4. SINKHOLES AT OLF SAN NICOLAS

NAS Jacksonville Taxiway Failure

1998

- EA-6B Prowler

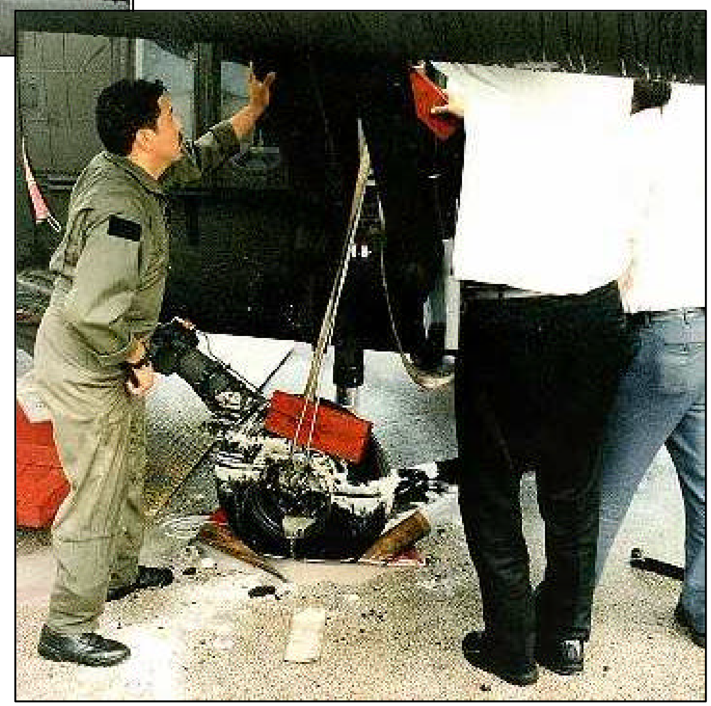
- Section TA/5 (now reconstructed)
- North of Hangar 117
- 3" AC
- 1998 PCI < 40
- A-6 ACN = 11 to 26
- Old clay pipe collapsing and leaking at joints

FIGURE 5. PAVEMENT FAILURE AT NAS JACKSONVILLE

NAS Jacksonville Taxiway Failure

1998

- UH-60 Black Hawk



- Section TA/5 (now reconstructed)
- North of Hangar 117
- 3” AC
- 1998 PCI < 40
- UH-60 ACN = 4.2 to 5.7
- Old clay pipe collapsing and leaking at joints

FIGURE 6. PAVEMENT FAILURE AT NAS JACKSONVILLE

NAS Corpus Christi Apron Failure

August 1985

- C-141 Starlifter
- 11” PCC
- South of Hangar 51

- Section AP1-4
- 1993 PCI = 65
- 1996 PCI = 10
- 1996 PCN = 7/R/C/W/T
- C-141 ACN = 41 to 65
- Sewer line in silty sand

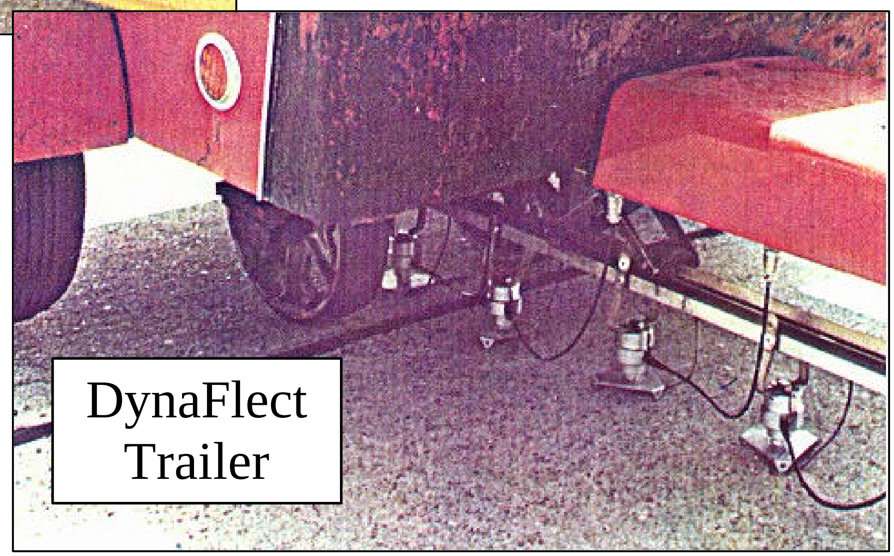


FIGURE 7. PAVEMENT FAILURE AT NAS CORPUS CHRISTI

Pavement sinkholes
(e.g. under sunken cone)
NAVSTA Everett, 1999

Pavement failure under a DC-9 main gear,
Manchester, New Hampshire Airport, 1990

Sinkholes on Runway 8-26
Capital City Airport, 1984

FIGURE 8. OTHER PAVEMENT FAILURES

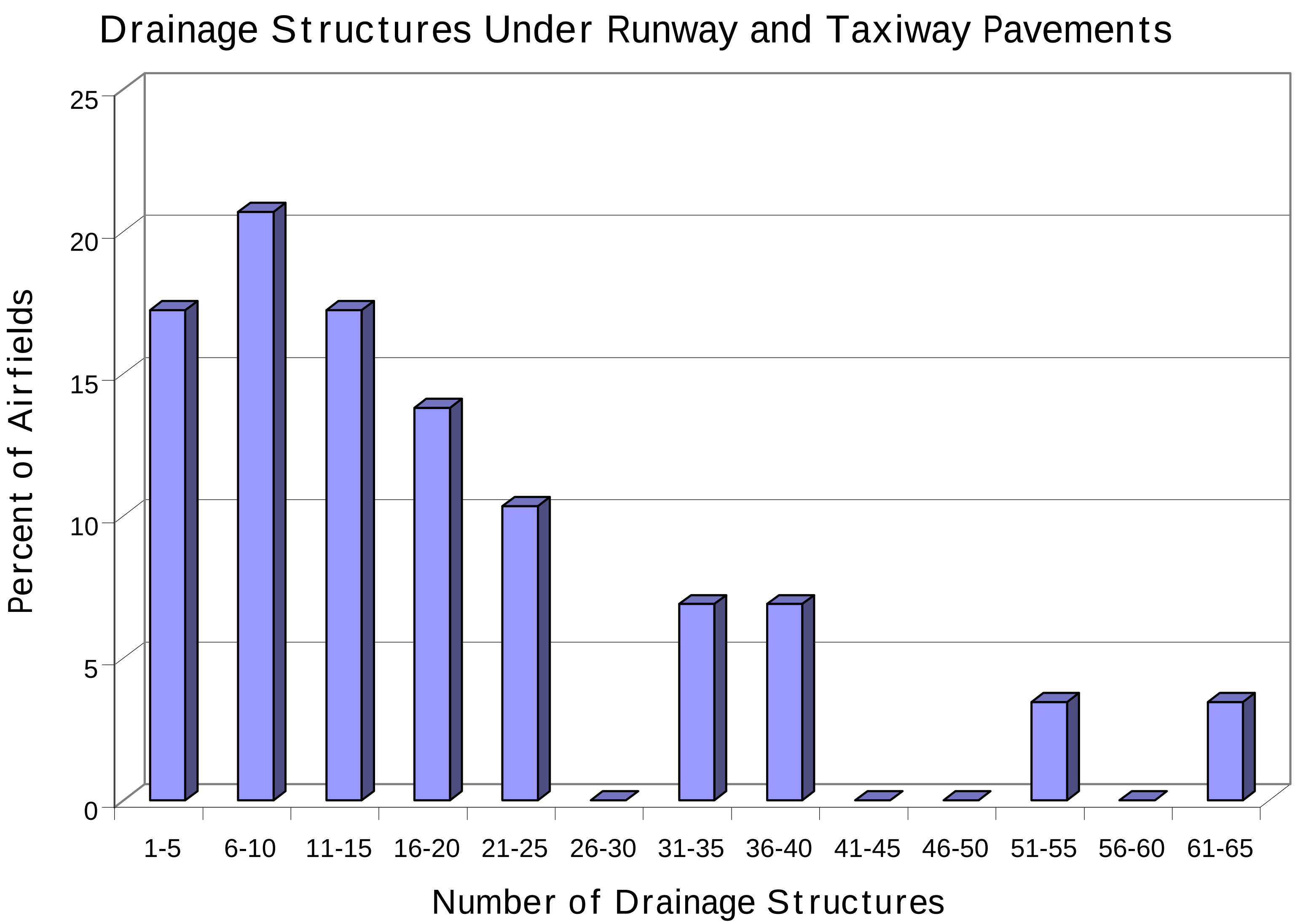


FIGURE 9. NUMBER OF DRAINAGE STRUCTURES UNDER RUNWAY AN TAXIWAY PAVEMENTS.

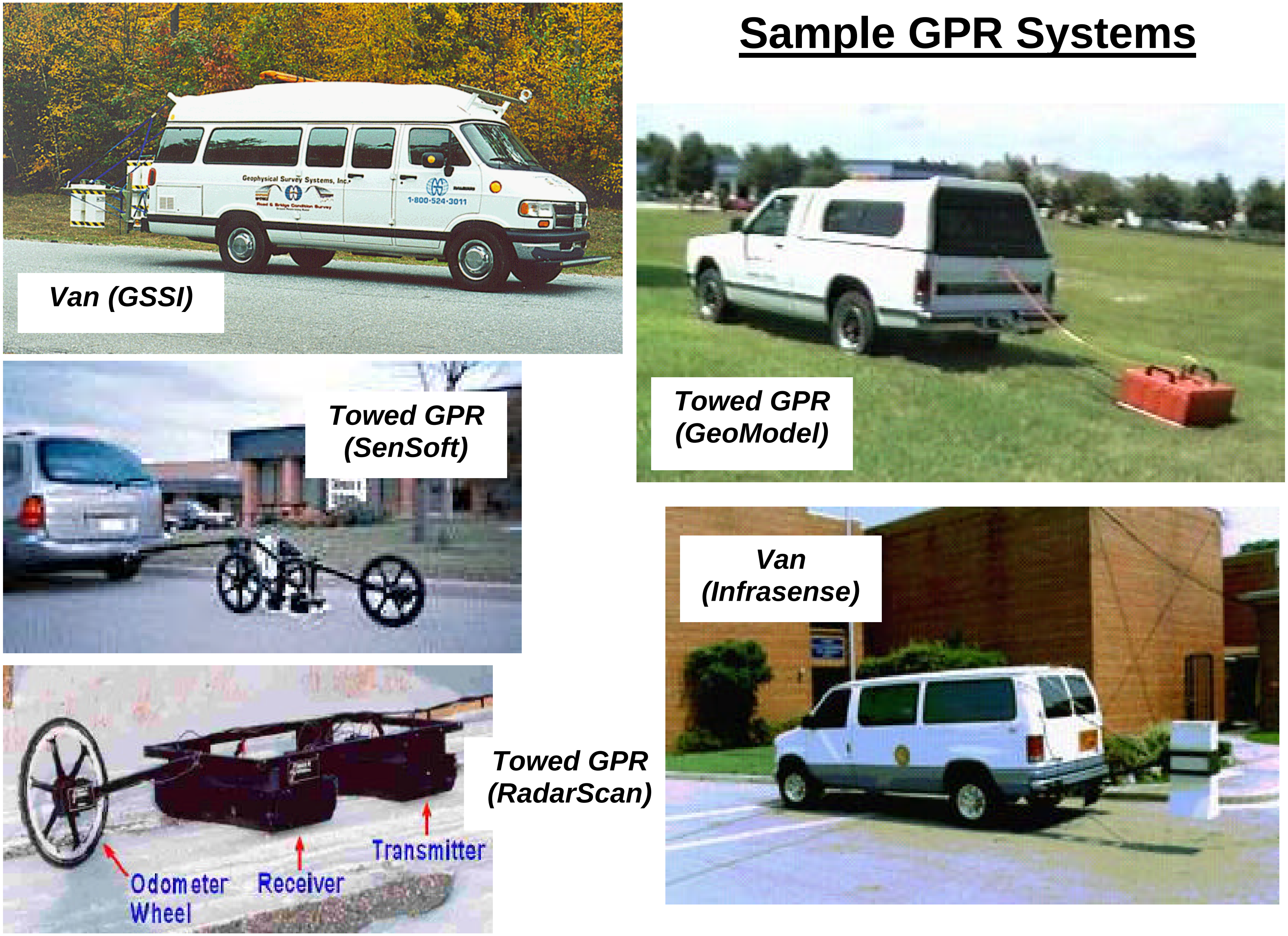


FIGURE 10. SAMPLE OF COMMERCIALLY AVAILABLE GPR SYSTEMS

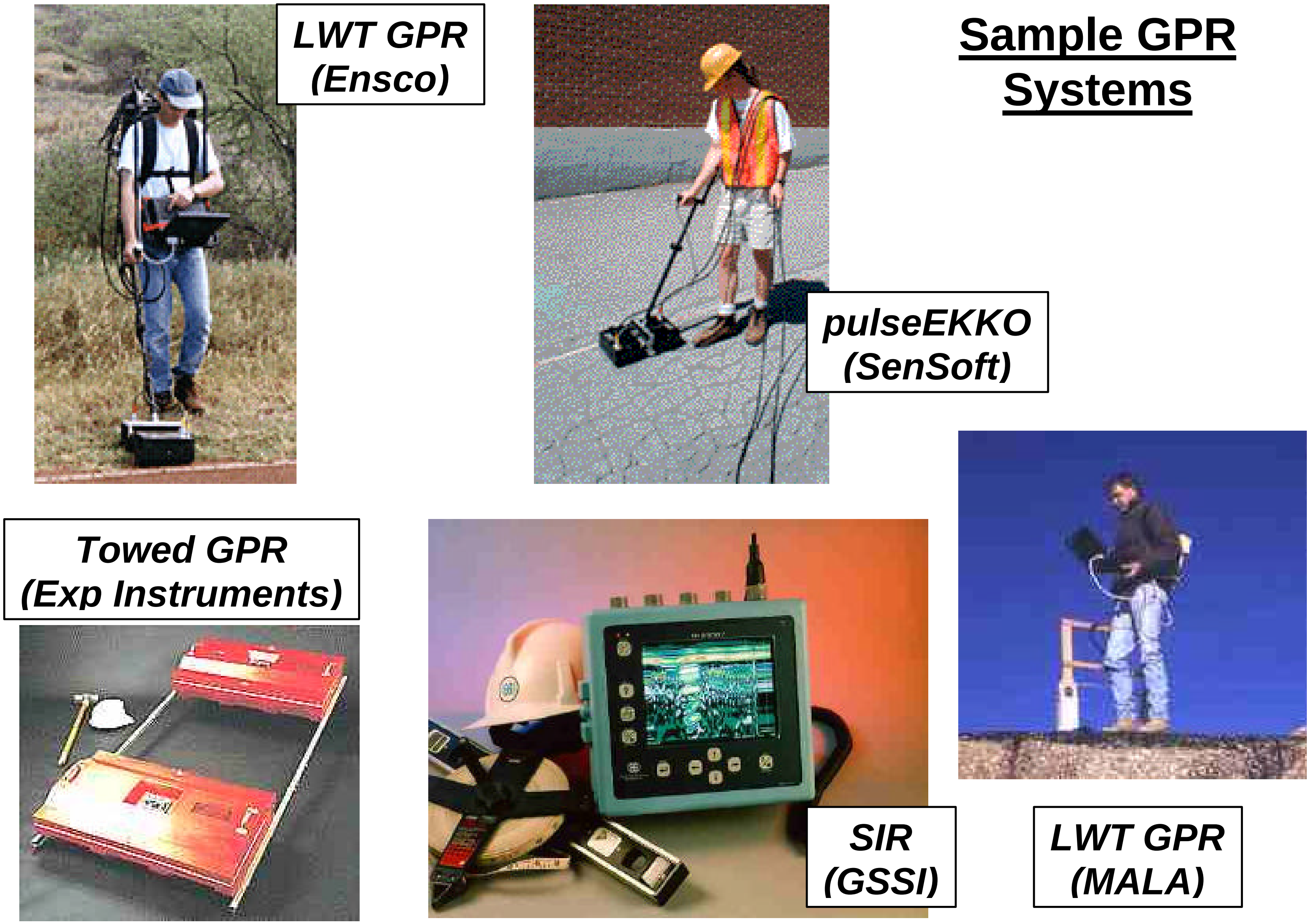


FIGURE 11. SAMPLE OF PORTABLE, COMMERCIALLY AVAILABLE GPR SYSTEMS

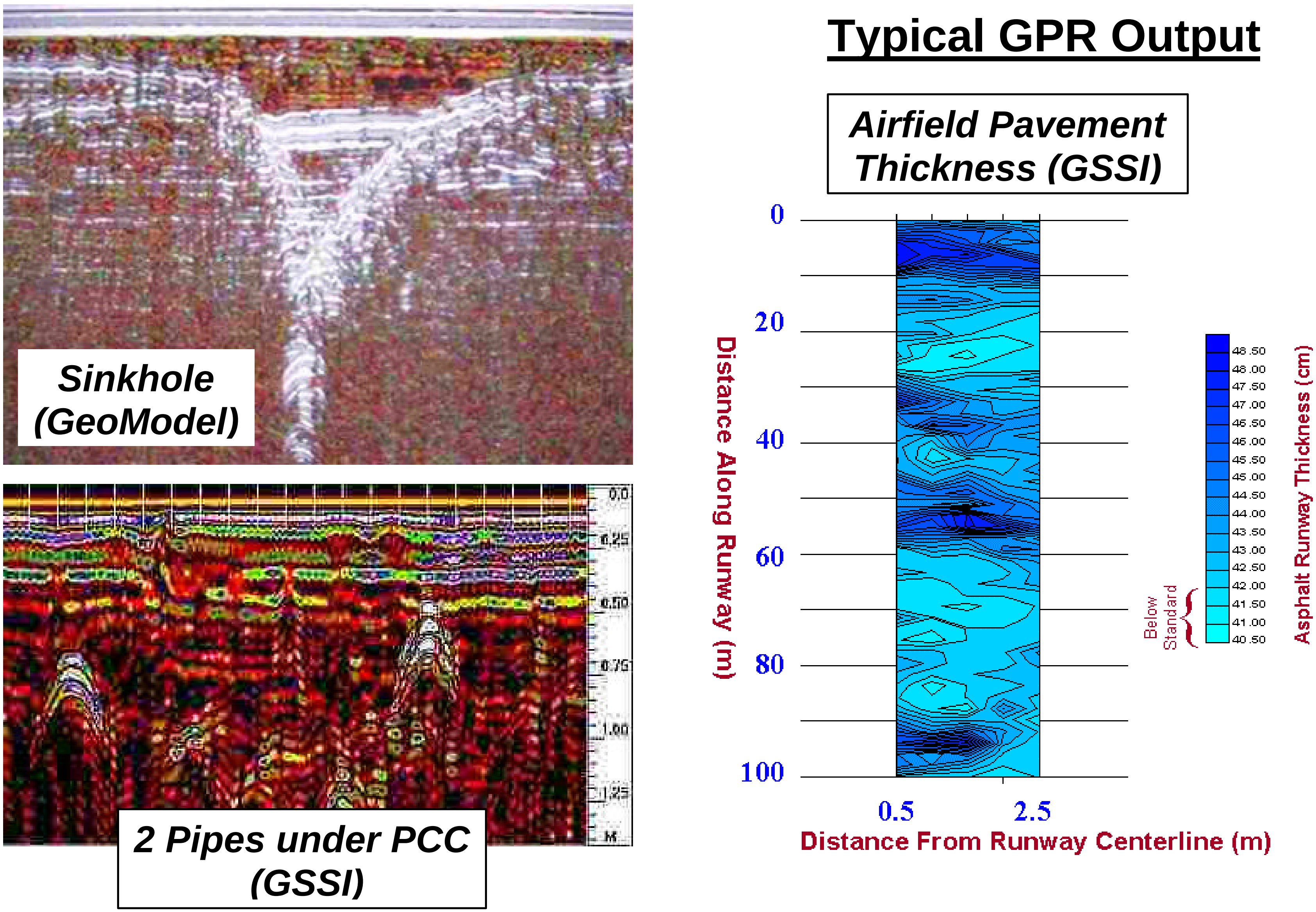
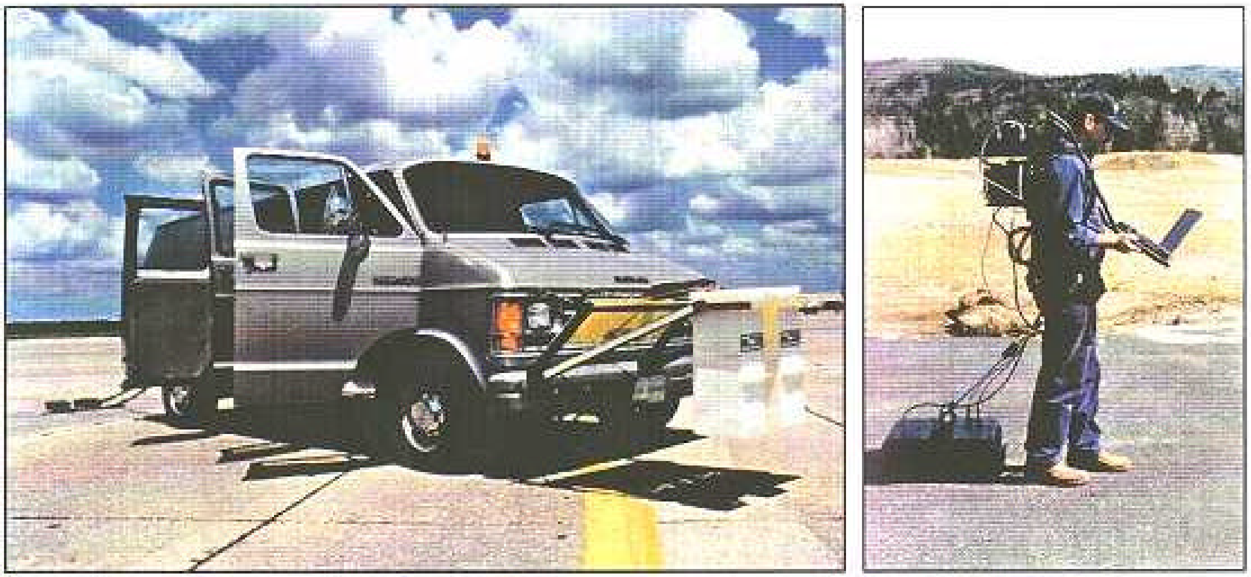


FIGURE 12. SAMPLE GPR OUTPUTS



(a) AFRL-MLQC van-mounted and portable GPR System.

(b) ERDC-WES four-antenna GPR System at NAS Pensacola
(with 250, 500, and 1000 MHz antennas in the front, and 100 MHz in the back).

FIGURE 13. AIR FORCE (AFRL-MLQC) AND ARMY (ERDC-WES) GPR SYSTEMS

APPENDIX A – IP&TG FOR VOID DETECTION

The following is a reprint of the Interim Policy and Technical Guidance for Void Detection that was issued by the Chief Engineer, NAVFACENGCOM, on 23 March 2000, based on work by NFESC and SOUTHDIV, and recommendations by the Tri-Service Pavement Team.

DEPARTMENT OF THE NAVY
Naval Facilities Engineering Command

23 Mar 00

From: Commander, Naval Facilities Engineering Command

Subj: NAVAL FACILITIES ENGINEERING COMMAND INTERIM POLICY AND TECHNICAL GUIDANCE FOR AIRFIELD PAVEMENT VOID DETECTION, REPAIR AND PREVENTION

Encl: (1) Amplification on NAVFAC Interim Technical Guidance for Airfield Pavements Void Detection, Repair and Prevention
(2) Naval Facilities Engineering Command Airfield Pavements Users Group

1. Purpose. To establish engineering policy and technical guidance to minimize the risk of subsurface voids to the structural integrity of airfield pavements, and reduce the probability of facility related hazards to aviation.

2. Policy. NAVFAC will maintain, and make available to aviation claimants, the best technology accessible through consultations and engineering services to facilitate the incorporation of void prevention and detection in airfield maintenance and renewal programs.

3. Background. Airfield pavements have failed under the load of taxiing aircraft because of undetected subsurface voids from soil erosion in the vicinity of drainage pipes. Such mishaps are extremely hazardous to life and aircraft. NAVFAC Engineering Field Divisions and the Naval Facilities Engineering Service Center, together with Public Works personnel, conduct periodic condition surveys for Claimants in managing their pavements. The current structural capacity and surface pavement condition evaluation protocols do not include explicit and mandatory inspections for subsurface erosion and related drainage conditions that cause voids.

4. Technical Guidance. Periodic inspections, using best available tools and experienced engineers, must be conducted at intervals consistent with the local susceptibility of airfields to void formation. Broken drainage pipes and excessive water entry to pavement foundation soils must be repaired and prevented to reduce the likelihood of void formation. Advanced technology shall be screened for unsubstantiated claims. NAVFC will accelerate development of appropriate technology. Enclosure (1) amplifies on methods, procedures, roles and responsibilities.

5. Funding. Claimant Maintenance and Repair (M&R) resources shall be used for activity specific consultations, engineering services, and for Claimant wide condition and structural surveys extended to include void detection and prevention. NAVFAC components shall assist and coordinate with Claimants in planning and programming for void surveys.

6. Action. NAVFAC components will initiate actions to assist Claimants in: (a) identifying their operational and technical requirements, (b) planning for resources for airfield void detection,

prevention and repair, (c) disseminating best available technology, and (d) selective development and validation of advanced technology.

7. Point of Contact. If you have questions, please call the local NAVFAC Engineering Field Division Pavement Team point of contact listed in enclosure (2). The NAVFAC Criteria Office Special Assistant for Pavement, Mr. Vince Donnally, can provide assistance in clarifying these policies and standards.

DR. GET W. MOY, P.E.
Chief Engineer and Director,
Engineering and Base Development

Distribution:
CO, PACNAVFACENGCOM
CO, LANTNAVFACENGCOM
CO, SOUTHWESTNAVFACENGCOM
CO, SOUTHNAVFACENGCOM
CO, NORTHNAVFACENGCOM
CO, ENGFLDACT WEST
CO, ENGFLDACT CHES
CO, ENGFLDACT NW
CO, ENGFLDACT MED
NFESC
NFESC East
CO, PWC WASHINGTON
CO, PWC PEARL HARBOR
CO, PWC GREAT LAKES
CO, PWC PENSACOLA
CO, PWC NORFOLK
CO, PWC SAN DIEGO
CO, PWC JACKSONVILLE
CO, PWC GUAM
CO, PWC YOKOSUKA

Copy to:
Internal List 1

AMPLIFICATION ON NAVFAC INTERIM TECHNICAL GUIDANCE FOR AIRFIELD PAVEMENTS VOID DETECTION, REPAIR AND PREVENTION
23 March 2000

Ref: (a) "Airfield Pavement Void Detection, NAS Pensacola," Site Specific Report SSR-2534-SHR, Naval Facilities Engineering Service Center, Port Hueneme, CA, December 1999, by Malvar, L.J., Lesto, J., Cline, G., and Beverly, W.

Attachment: (1) Naval Facilities Engineering Command Airfield Pavement Users Group

Purpose. Provide methodology and technical guidance for determining the risk of pavement failure from undetected subsurface voids. The assessment is intended for application at all Navy and Marine Corps airfields. The objective is to provide cost-effective and reliable methods to minimize the potential for accidental airfield pavement failure due to subsurface voids.

Background. Pavement failure due to subsurface voids has resulted in aircraft accidents at Navy airfields, causing concerns for potential accident and threat to life safety in the future, as facilities age and resources for maintenance and repair become more scarce. Reference (a), available at http://intranet.nfesc.navy.mil/apvdt.htm, describes recent evaluation of available technology using tri-service equipment and personnel in the development of a methodology to detect such subsurface weaknesses. The approach used a combination of destructive and non-destructive testing. While the detection protocols that emerged are specifically addressed to pavements above drainpipe crossings, the methods can be applied elsewhere.

Technical Guidance.

1. Void Detection

a. Visual inspection of the airfield pavements should be performed with frequency sufficient to locate potential problem areas and satisfy the airfield manager its operational safety. Such inspections shall monitor pavements for conditions that may affect aircraft movement (FOD, depressions, pavement deterioration, etc.). Frequency should be determined by local physical conditions and operational tempo as to minimize the hazards. In flexible pavements, depressions are evident after a rainfall, or by the concentric marks left by the evaporated water. In rigid pavements, standard 12½ by 15-ft concrete slabs cracked into two or more pieces, as well as slabs that exhibit faulting at joints, may indicate underlying soft spots or voids. In particular, areas above drainpipe crossings should be carefully inspected since most problems appear near these pipes. Problems observed in unpaved areas above a pipe are early warning signs of problems in nearby paved areas above the same pipe. Depressed pavement or shattered slabs surrounding drainage structures (catch basins) indicate infiltration of soil materials into the structure or pipe. Visual inspections can also follow Pavement Condition Index (PCI) guidelines,

Enclosure (1)

as detailed in NAVFAC MO-102 Manuals, and as detailed in ASTM Standards commonly available.

b. If visual inspection suggests concern, further evaluation using a Heavy Weight Deflectometer (HWD) should be performed. The HWD investigation would cover all pipe crossings and additional suspect areas, following the procedure indicated in SP-2534-SHR. It can be found on the website http://intranet.nfesc.navy.mil/apvdt.htm. The HWD will establish the effect of any subgrade weakness (or void) on the load-carrying capacity of the pavement. HWD evaluations can be performed by the cognizant NAVFAC Engineering Field Division Airfield Pavement Design/Evaluation Team listed in enclosure (2). Periodic testing with a HWD is recommended at all pipe crossings. This HWD testing can be completed at the same time as the standard Pavement Classification Number (PCN) structural evaluation cycle, as described in Headquarters, Department of the Army, Air Force and Navy, "Airfield Pavement Evaluation" Technical Manual, TM 5-826-1/AFJMAN 32-1121/DM 21.7, Washington, DC, December 1998.

c. Weak areas revealed by the HWD should be further tested to determine the depth of the weakness in order to determine the type of repair needed. This testing can be completed using either a Dynamic Cone Penetrometer (DCP), Electronic Cone Penetrometer (ECP), or Standard Penetration Test (SPT). Video taping the interior of pipe crossings is recommended when testing and/or visible failure is evident in or around pipe crossings. It will help pinpoint the location of potential problem areas and define the need for maintenance and repair. Special attention should be paid to assessing pipe crossings and joints. Accumulations of fines near joints or other penetrations are a good indicator of a loss of subgrade material and possibly subgrade strength. Naval Facilities Engineering Command "Design Manual 21.06 – Airfield Pavement Design for Frost Conditions and Subsurface Drainage" draft August 1999 (final expected to be issued by May 2000) provides discussion on video inspection of subsurface drainage utilities. In some cases, coring of the pavement may be required to confirm presence of voids directly below the pavement surface.

d. Alternate non-destructive techniques are currently being evaluated, but are not believed to be as effective as the aforementioned tools in determining the existence of voids. Ground Penetrating Radar (GPR) cannot be used as a reliable tool to predict weak areas and GPR should not be used for void detection at this time. However, GPR appears successful in locating the actual location of drainpipes and thickness of pavement layers, and potentially could be used to verify the extent of known voids.

e. Based on experience to date approximately, and in the absence of more specific information, approximately $75,000 should be used for programming purposes for a one-time evaluation of all drainage pipe crossings of typical air stations.

2. <u>Void Repair and Prevention</u>

a. Repair methods are now available from the cognizant NAVFAC Engineering Field Division Pavement Design/Evaluation Team. Methods include pressures grouting, excavation, filter materials, compaction, and quality control

b. Designs and practices to prevent the onset or growth of voids are also available from the cognizant NAVFAC Engineering Field Division Pavement Design/Evaluation Team.

c. Because of the complex nature of the hydrologic and geotechnical aspects of subsurface erosion and the threat of undetected voids to high value manned aircraft, work of void prevention, detection and repair should be considered Type 1 (as per NAVFAC Policy document dated 31 December 1998) in order to draw from the cumulative experiences of several EFD/NFESC specialists.

NAVFAC components will:

(1) Make available expert technical assistance to air stations in implementing visual inspections and interpretation procedures.
(2) Make available to air stations the EFD/NFESC combined HWD and DCP capability to detect the location and severity of voids/soft conditions in the pavement foundation soils when needed
(3) Make available to air stations consulting services for the development of a risk and cost based plan for inspection, prevention and repairs to reduce hazards from undetected conditions.
(4) Recommend, in the absence of other compelling reasons, the conduct of complete evaluation of all pavements, at drainage pipe crossings when performing (every 8 years) the PCN structural evaluation survey. This will establish the risk prioritization and requirements for funding.
(5) Periodically validate claims of advanced technology, demonstrate suitability for adoption and use, and collaborate with research and development organizations for selective and focused development – generally in concert with the Tri-Service Pavements Group.
(6) Maintain appropriate cost data and provide to stations economic basis for actions.
(7) Pursue the maintenance of reciprocal, interdependent and sharing practices to optimize the accumulation of experience (for core competence learning) and the distributed availability of knowledge for use minimally within the DON and ultimately among public airfield operators and engineers.
(8) Maintain an effective, easily accessible database of knowledge an criteria along with other airfield engineering information.
(9) Report all conditions suggesting water entry, erosion, softness, loss of load capacity, and voids to air station and EFD authorities for Type 1 response action.
(10) Disseminate this guidance document to all aviation claimant commands and their activity level pavement engineers.

<u>Points of Contact</u>. If you have questions, enclosure (2) provides the NAVFAC Engineering Field Division Pavement Design/Evaluation Team.

Enclosure (1)

NAVAL FACILITIES ENGINEERING COMMAND
AIRFIELD PAVEMENT USERS GROUP POINTS OF CONTACT
23 March 2000

Name/Code	Address	E-mail	Telephone
Vincent Donnally NAVFAC Code 15	Naval Facilities Engineering Command NAVFAC Criteria Office 1510 Gilbert Street Norfolk, Va. 23511-2699	Donnallyvr@efdlant.navfac.navy.mil	(757) 322-4204
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Darrell Bryan NAVFAC LANTDIV	Atlantic Division Naval Facilities Engineering Command 1510 Gilbert Street Norfolk, Va. 23511-2699	BryanDG@efdlant.navfac.navy.mil	(757) 322-4411
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Dr. Javier Malvar NFESC Code 63	Commanding Officer NFESC Code 63 1100 23RD Ave. Port Hueneme, CA 93043-4370	Malvarlj@nfesc.navy.mil	(805) 982-1447
Charles J. Schiavino NFESC Code 63	Naval Facilities Engineering Command Northern Division 10 Industrial Highway Mail Stop #82 Lester, Pa. 19113-2080	Schiavinocj@nfesc.navy.mil	(610) 595-0597
Wilbert Beverly NAVFAC SOUTHDIV	Naval Facilities Engineering Command Southern Division 2155 Eagle Drive North Charleston South Carolina 29418	Beverlyw@efdsouth.navfac.navy.mil	(843) 820-7352
Noland Araracap NAVFAC SOWESTDIV	Naval Facilities Engineering Command South Western Division 1220 Pacific Highway San Diego, California 92132	AraracapNA@efdsw.navfac.navy.mil	(619) 532-4646

Enclosure (2)

NAVAL FACILITIES ENGINEERING COMMAND
AIRFIELD PAVEMENT USERS GROUP POINTS OF CONTACT
23 March 2000

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Mike Tsuru NAVFAC PACDIV	Naval Facilities Engineering Command Pacific Division Building 258 Makalapa Dr., Suite 100 Pearl Harbor Hawaii 96860	TsuruMT@efdpac.navfac.navy.mil	(808) 474-5382
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Eldon M. Jemtrud EFA West	Naval Facilities Engineering Command Engineering Field Activity West Naval Facilities Engineering Command 800 Commodore Drive San Bruno, CA 94066-2042	emjemtrud@efawest.navfac.navy.mil	(650) 244-2743 DSN 494-2743
Dennis Scheessele EFA Chesapeake	Naval Facilities Engineering Command Engineering Field Activity Chesapeake Washington Navy Yard 851 Sicard Street SE Washington, DC 20374-5018	Scheesseledj@efaches.navfac.navy.mil	(202) 685-3131

Enclosure (2)

APPENDIX B – PARTIAL LIST OF GPR PROVIDERS

The list below provides direct access to the website of each company. Additional links and link sources are available under the following links included below:

- David Noon's GPR Links
- Lawrence Livermore National Laboratory Landmine Who's Who

The fifty or so links below will then provide access to hundreds of web site locations for GPR providers, researchers, centers and conferences (some are real interesting, e.g. check out http://www.enviroscan.com/techapps.html).

Click on http:// to access web site

1. Advanced Geological Services

Corporate Headquarters	Baltimore/DC	Florida
3 Mystic Lane	15 Sugartree Place	2431SE Dixie Highway
Malvern, PA 19355	Cockeysville, MD 21030	Stuart, FL 34996
610-722-5500	410-667-7522	561-287-0525
Fax: 610-722-0250	Fax: 410-667-7522	Fax: 561-220-8686

advanced@net-thing.net
http://www.advancedgeo.com/groundradar.html

2. American Geological Services Inc.,
3222 S. Vance St., Suite 100
Lakewood, Colorado 80227
(303) 988-1845
Fax (303) 986-2898
ags@rmi.net
http://www.amer-geo.com/srvgeoph.htm

3. Applied Radar Inc.
14 Union Street, Watertown, MA 02472
617-924-1009
FAX: 617-924-0337
whw@appliedradar.com
http://www.appliedradar.com/GPR.htm

4. Applied Solutions Group
320 East Main Street, Suite 201A
Murfreesboro, TN 37130
FAX (630) 214-4645
appliedsolutions@mindspring.com**{**PRIVATE "TYPE=PICT;ALT=e-Mail"**}**

http://www.asgi.net/2000pg10.htm

5. Arctic Geoscience Inc.
Postal address
1000 O'Malley Drive, Anchorage, Alaska 99515
907-522-4300
Fax: 907-522-4301
agsimail@arcticgeo.com
http://www.arcticgeo.com/web_pdf/gpr.pdf

6. AASHTO Innovative Highway Technologies
http://leadstates.tamu.edu/dbtw-wpd/exec/dbtwpub.dll

7. BOMBS AWAY, Inc.
388 South Marine Drive, #102-117
Tamuning, Guam USA 96911
Fax/Phone (671) 789-7887
murray@ite.net
http://www.bombsaway.net/geo.htm

8. Construction Technology Laboratories
5420 Old Orchard Road
Skokie, Illinois 60077-1030
Chicago Area: (847) 965-7500
Outside Chicago Area: (800) 522-2285
Fax: (847) 965-6541
Special_Inquiries@C-T-L.com
http://www.c-t-l.com/

9. CRREL
Cold Regions Research and Engineering Laboratory
USACE Engineer Research and Development Center
http://www.crrel.usace.army.mil/cerd/

10. David Noon's GPR Links
http://www.cssip.elec.uq.edu.au/~noon/gprlist.html

11. Detection Sciences, Inc.
496 Heald Road
Carlisle, Massachusetts 01741-1418
(978) 369-7999
Fax: (978) 369-4497

12. EMRAD Ltd.
Pipe Hawk Ground Probing Radar System
9 Fleet Business Park, Sandy Lane, Church Crookham, Hampshire, GU13 0BF, UK

Tel: +44(0)1252 628880
Fax:+44(0)1252 625556
Mike Bushell Sales/Marketing Director *+(44) 01252 628880 FAX+(44) 01252 625556*
{PRIVATE**}**James Lewis Intl. Distributor Manager *+(44) 01252 628880 FAX+(44) 01252 625556*
EMRAD Ltd.
http://www.emrad.com/

13. ENSCO
Springfield, VA
703-321-9000
info@ensco.com
http://www.ensco.com/Projects/gpr.htm

14. Entech Engineering, Inc.
111 Marine Lane
St. Louis, MO 63146
Contact: Gary Weil
(314) 434-5255, Fax (314) 434-3270
garyjweil@entech.mdt.com
http://www.geophysical.com/missouri.htm

15. Enviroscan, Inc.
1051 Columbia Ave.
Lancaster, PA 17603
(717) 396-8922, Fax: (717) 396-8746
email@enviroscan.com
http://www.enviroscan.com/radar.html and http://www.enviroscan.com/techapps.html

16. Exploration Instruments LLC
4807 Spicewood Springs Road, Bldg. #2
Austin, Texas 78759
Voice Phone - (512) 346-4042
FAX - (512) 346-0088
info@expins.com
http://www.expins.com/gpradar.htm

17. FHWA
For more information on using GPR on concrete bridge decks or borrowing the GPR van, contact Donald Jackson at 202-366-6770; fax: -7909; donald.jackson@fhwa.dot.gov). For more information on the use of GPR technology to measure pavement layer thickness, contact Sonya Hill at FHWA (202-366-1337; fax: 202-366-3713; sonya.hill@fhwa.dot.gov).
http://www.fhwa.dot.gov/

18. Geo-Centers, Inc.

7 Wells Avenue
Newton Center, MA 02159
(617) 964-7070
Fax (617) 527-7592
adean@tech.geo-centers.com
http://www.geo-centers.com/

19. Geo-Graf, Inc.
511 Beechwood Drive
Kennett Square, PA 19348-1803
Toll Free: (800) 690-3745
Fax: (610)444-3191
info@geo-graf.com
http://www.geo-graf.com/

20. Geoinstruments
348 Rocky Point Road, Ramsgate
NSW 2217 Sydney AUSTRALIA
Ph: +61 2 9529 2355 Fax: +61 2 9529 9726
info@geoinstruments.com.au
http://www.geoinstruments.com.au/

21. GeoModel, Inc.:
5728 Major Boulevard, Suite 200
Orlando, FL 32819
Phone: (407) 578-9563
Fax: (407) 290-6891
geomodel@geomodel.com
http://www.geomodel.com/

22. Geophysical Survey Systems Inc.
Member Oyo Group
13 Klein Drive, North Salem, NH 03073
Ph: (603)893-1109Fax: (603)889-3984
sales@geophysical.com
http://www.geophysical.com/

23. Geophysics GPR International
2545, Delorimier St.
Longueuil, Québec
J4K 3P7 Canada
450-679-2400
Fax: 514-521-4128
gprmtl@citenet.net
http://www.geophysicsgpr.com/index.htm

24. GeoRadar Inc.
19623 Via Escuela Drive
Saratoga, CA 95070 U.S.A.
phone 408-867-3792, fax 408-867-4900
dcrice@georadar.com
http://www.georadar.com/

25. Geosphere, Inc
3800 Gettysburg Midland, MI 48642
tel: **(517) 832-8626**
fax: (517) 832-8631
consultants@geosphereinc.com
http://www.geosphereinc.com/gpr.htm#profile

26. GEOVATION
468 Route 17A, P.O. Box 293
Florida, NY 10921
Phone: (914) 651-4141
Fax: (914) 651-0040
info@geovation.com
http://www.geovation.com/gprmain.htm

27. GEOvision Geophysical Services
1785 Pomona Road, Suite B
Corona, CA 91720
(909) 549-1234
Fax (909) 549-1236
Info@geovision.com
http://www.geovision.com/case.htm

28. Ground Penetrating Radar
8391 Beverly Boulevard #134
Los Angeles, CA 90048
Phone: (407) 297-8101, Fax: (407) 290-6891
gprsurveys@groundpenetratingradar.com
http://www.groundpenetratingradar.com

29. GROUNDSEARCH (NZ) –GEOPHYSICS AUSTRALIA
PO Box 15-038, New Lynn
3061b Gt North Rd, New Lynn Auckland New Zealand
Phone +64-9-826-0700, FAX +64-9-826-0900
k.thompson@groundsearch.co.nz
http://www.groundsearch.co.nz/Radar.htm

30. Harris Technologies Inc.
2431 Beekay Court

Vienna, VA 22181
(703) 2559456, Fax: (703) 3191439
drjch@sprintmail.com

31. IDS Italy
Via Flaminia, 330
I-00196 Roma - Italy
Ph.: +39 06 36002443
Fax: +39 06 36002447
idsroma@ids-spa.it
http://www.ids-spa.it/georadar/sitoris/geordiv.htm

32. Infrasense, Inc.
14 Kensington Road Arlington
MA 02476-8016 USA
(781) 648-0440 , Fax: (781)648-1778
info@infrasense.com
http://www.infrasense.com/pavepage.htm

33. Interpex
P.O. Box 839
Golden • Colorado • 80401 • USA
Tel (303) 278-9124 • Fax (303) 278-4007
sales@interpex.com
http://www.interpex.com/radar.htm

34. KD Jones Instrument Corporation
P.O. Box 750
Normangee, TX 77871
(888) 396-9291, Fax (409) 396-6524
http://www.kdjonesinstruments.com/links.html

35. Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550-9234
http://www.llnl.gov/str/Hernandez.html

36. Lawrence Livermore National Laboratory
Landmine Who's Who
7000 East Avenue, Livermore, CA 94550-9234
http://www.llnl.gov/landmine/landmine_whos_who.html

37. MALÅ GeoScience USA Ltd.
Airpark Business Center
400 Harvey Road
Manchester, NH 03103, USA

Telephone: +1 603 627 5841 +1 888 USA MALA
Facsimile: +1 603 627 5874
sales.usa@malags.se
http://www.malags.se/

38. Northeast Geophysical Services
4 Union Street, Suite 3
Bangor, Maine 04401
ngs@agate.net
http://www.agate.net/~ngs/ngs.html

39. Nortech Geomatics Inc.
1,4001A 19 Street N.E.
Calgary, Alberta, CA, T2E 6X8
403-291-3333
Fax: 403-291-3688
info@nortech-geomatics.com
http://www.nortech-geomatics.com/main.html

40. Planning Systems Inc
115 Christian Lane
Slidell, LA 70458
(504) 649-0450
marshall.bradley@psislidell.com

41. Radarscan Inc.
Ground Penetrating Radar Surveys
Ian Harding B.Sc., Geology Cell Phone: (403) 803-6188
Ken Blair, Civil Eng. Technologist, Chris Kirchner, M.A., Geography
Office Phone: (403) 286-3219 Fax: (403) 286-1407
Address: C4 - 1700, Varsity Estates Drive N.W., Calgary, Alberta, Canada, T3B 2W9
info@radarscan.com
http://www.radarscan.com/GPR.htm#GPR

42. Sensors & Software Inc.
1091 Brevik Place
Mississauga, ON L4W 3R7 Canada
Phone: (905) 624-8909, Toll free Canada & USA: (800) 267-6013
Fax: (905) 624-9365
web@sensoft.on.ca
http://www.sensoft.on.ca/

43. SRI International Offices
333 Ravenswood Ave.
Menlo Park, CA 94025-3493

650-859-2000
Fax: 650-326-5512
info@rsed.sri.com
http://www-gec.sri.com/wideband.html

44. Sub-Surface Informational Surveys, Inc.
PO Box 759
Somers, CT 06071-0759
bacan@gte.net
http://subsurfaceinc.com/

45. Surface Search Inc.
700, 700 - 6 Ave. SW
Calgary, Alberta
Canada T2P 0T8
Tel (403) 531-9721, Fax (403) 294-1162
Email Surface Search Inc.
http://www.surfacesearch.com/whoweare/gpr.html

46. Tampa Bay Engineering, Inc. / TBE Group, Inc.
18167 U.S. 19 North, Suite 550
Clearwater, Florida 33764
(800) 861-8314 or (727) 531-3505
Fax (727) 539-1294
tbe@tbegroup.com
http://www.tbegroup.com

47. Techno Soft (Penetradar Integrated Radar Inspection System)
FO-826 Trongisvagur
Færøerne, Denmark
70 20 55 46
technosoft@software.dk
http://www.technosoft.dk/rdrdown.htm

48. Terraplus USA
625 Valley Road, Littleton, CO 80124
(800) 553-0572 or (303) 799-4140
Fax: (303) 799-4776
http://www.terraplus.com/gprdetails.htm

49. United Consulting
625 Holcomb Bridge Road
Norcross, Georgia 30071
(770) 209-0029
Fax (770) 582-2900
http://www.unitedcg.com/gpr.htm

50. U.S. Army, Waterways Experiment Station, Geotechnical Laboratory
Vicksburg, MS
http://pavement.wes.army.mil/

51. University of Cape Town, South Africa
Radar Remote Sensing Group
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52. USGS

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http://geology.cr.usgs.gov/capabilities/geoanal/grndrad/contacts.html

Responses via BAA:

Detection Sciences Inc.	Geophysical Survey Systems Inc.	Harris Technologies, Inc.
Planning Systems, Inc.	Sensors and Software, Inc.	